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Technical and Economic Factors Associated with Fly Ash Utilization

71 JUL 26

Prepared for SPECIAL PROJECTS SECTION
DIVISION OF CONTROL SYSTEMS
OFFICE OF AIR PROGRAMS
ENVIRONMENTAL PROTECTION AGENCY

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FOREWORD

The study of the technical and economic factors associated with fly ash and limestone-modified fly ash involves many different types of industries, technologies, agencies and individuals, such that the results given herein cover a broad range of data and interests. To simplify the reading of the results, a comprehensive summary of the study is provided in Section 1. Included in that section is a statement of conclusions, Section 1.3, and a listing of recommendations for future efforts necessary to improve the fly ash market, Section 1.4. The main body of this report is presented in Sections 4 and 5. These provide the basic details of the survey and study efforts of this program. Supporting data and listings of relevant literature and data sources are given in the appendices.

The period of performance for this study was October 1970 through June 1971.

Appreciation is acknowledged for the assistance and guidance provided by Dr. J.S. Bowen and Mr. T.A. Kittleman of the Environmental Protection Agency, Office of Air Programs, Division of Control Systems, Special Projects Section (formerly Process Research Section), for whom this study was conducted.

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SECTION 1

SUMMARY

1.1 SCOPE OF THE STUDY

This report contains the results of a study performed to determine characteristics pertaining to the current and potential use of fly ash, the particulate residue produced from burning pulverized coal. Because of the great number and variety of industries and individuals involved in total production and use of fly ash, this study was directed toward that produced by the coal burning power utilities. This constitutes the major portion of fly ash produced in this country and is the source of ash collected and sometimes used as a raw material for various products or applications. Presently, of the 26.5 million tons produced annually, approximately 1.6 to 2 million tons are utilized. Additionally, the power utilities have in some instances installed systems to remove gases of sulfur which result from coal combustion. Some of these systems employ wet limestone scrubbing of the resulting fly ash and effluent gases. This process appreciably modifies the fly ash such that it is not amenable to most utilization schemes to which the unmodified (regular) fly ash is applied, and it increases the amount of fly ash produced by as much as one and one-half to three times. This process, if widely used, could have an appreciable impact on the existing and potential unmodified fly ash market.

The objectives ~~of this study~~ were to investigate the current and potential uses of regular fly ash and to: (a) identify the factors which inhibit its use, (b) investigate the applicability of substituting wet-limestone-modified fly ash in the regular fly ash market, and (c) make recommendations for developing both the regular and wet-limestone-modified fly ash markets.

1.2 STUDY APPROACH AND PROCEDURES

It has been established through development and actual practice that fly ash is a valuable mineral resource and as such has been successfully used in numerous applications. However, this usage has been rather limited (i.e., 1.5 to 2.0 million tons per year over the past four years), and does not show any sign of attaining rapid advancements. Although the possibility of new discoveries or developments was not neglected in this study, the principal approach taken to investigate inhibitions and potential uses of the regular ash was to consider those uses for which it is already applied and where the use could consume large quantities of fly ash. New or modified developments, however, are a significant factor in the assessment of modified ash utilization.

The production and utilization of fly ash involves many organizations and individuals throughout varying geographic regions of the United States. Therefore, since no set conditions or circumstances are generally applicable to all cases, it was necessary to select significant circumstances and relate them to the appropriate organizations and geographic areas as best suited to the attainment of the objectives of this study. The emphasis of these efforts was placed on what is best for the nation as a whole and not necessarily on what may be desired in isolated areas.

The review of limestone-modified fly ash was limited to the ash produced by the wet limestone process. Other systems produce a dry limestone-modified ash which has been studied in other programs in considerable detail (see Section 5.1).

The major portion of this study was directed toward the production and utilization of regular fly ash. In addition to its being a principal consideration in the objectives of this study, an understanding of fly ash, of the inhibitions to its use, and of its present and potential market are basic to the determination of the potential utilization of modified fly ash. This is due to the fact that for many uses conceived for the modified ash, its marketing processes will be similar to those of regular ash. This relationship, when considering use inhibitions, should appreciably aid the determination of: (a) the efforts to be expended on modified ash developments for existing fly ash uses, (b) the necessity for developing new uses, and (c) the methods and potential of marketing modified ash.

After the foregoing study approach was established, the study was conducted according to the following procedures:

1. Review the literature pertaining to fly ash production, utilization, technology, and marketing.
2. Review the status of fly ash production, utilization, technology, and marketing with individuals significantly involved with fly ash in power plant operation, sales, research and development, product manufacture, product use, trade associations, technical societies, and government agencies. (A list of these contacts can be found in Appendix B.)
3. Determine fly ash uses having high technical utilization potential and assign priorities for further study.
4. Analyze current and potential use inhibitions on the basis of technology, economics, and producer and user attitudes.
5. Make recommendations for improvement of fly ash market.
6. Review known and projected qualities of wet-collected limestone-modified fly ash.
7. Determine potential uses for modified ash and estimate its use inhibitions and impact on regular ash market.
8. Make recommendations for the programs or tasks which should be performed for development of a modified ash market.

1.3 SUMMARY OF RESULTS, AND CONCLUSIONS

Although fly ash is used in various applications, those utilizations consume only a small portion of the total amount of fly ash available. Through a review of the current technology via the literature and through contacts with individuals in the industry, an estimation was made of the amount of fly ash that could be technically utilized in the various applications used today regardless of any other circumstances such as supply, economics, etc. This was done for the purpose of identifying those areas that could best benefit from the increased mass utilization of fly ash, thereby indicating where effort, if any, should be applied for the improvement of the market. Maximum technically feasible uses of at least one million tons per year are listed in Table 1-1, column 1. It should be noted that this is based on ash composition and possible product utilization alone. The 1970 actual utilization values for each use are listed in column 2, and total 1.6 million tons per year. As a result of this survey, it is estimated that if fly ash were used in the applications listed in Table 1-1 such that the maximum practical potential would be utilized under current technology and associated market conditions, approximately 7 million tons would be utilized, as shown in column 3. It must be realized, for clarity, that this study was not a marketing analysis and that these values are merely best estimates. The significance of this list is that it indicates approximately 75 percent of the fly ash produced in the United States is not marketable without significant changes being made to reduce or eliminate the following limitations: (a) inadequate technology and knowledge dissemination related to known uses, (b) geographic limitations on transportation economics, (c) insufficient marketing efforts, (d) lack of control of fly ash production and supply, (e) cost effects of other materials or processes, and (f) insufficient development of new technologies.

The values given in column 4 of Table 1-1 are estimates of the amounts of fly ash that would be consumed if all the limitations just noted were removed, except some geographic limitations on transportation. These factors are discussed in detail in Section 4 of this report. Again, these values are estimates, but they indicate areas where it is believed fly ash can be used in large quantities if appropriate steps are taken. This approach limits the area of concern to: (a) fly ash concrete, (b) lightweight aggregate, (c) road base courses, (d) new uses or developments such as gas concrete building construction, ceramic products, and mineral recovery, and (e) control of mine subsidence and fires.

Table 1-1. Estimated Fly Ash Utilization Potential
(Million Tons Per Year)

	1	2	3	4[*]
			Estimated Utilization Potential	
Use	Maximum Utilization Technically Feasible	1970 Utilization	Current Conditions	Improved Utilization
Fly Ash Concrete (Structural, Mass and Concrete Products)	10-15	0.54	3.5	6.0[**]
Lightweight Aggregate	13	0.21	0.5	>3.0[***]
Raw Material for Cement	13	0.16	0.25	[****]
Bricks	10	----	----	----
Filler in Bituminous Products	1-2	0.13	0.75	[****]
Base Stabilized for Roads	> Annual Production	0.11	0.3	>10.0
Agriculture and Land Reclamation	> Annual Production	----	----	----
Control of Mine Subsidence and Fires	>1	0.01	0.75	>1.0
Structural Fill for Roads, Construction Sites, Land Reclamation, etc.	> Annual Production	0.32	0.6	[****]
Others	----------	0.16	0.25	[*****]
Total (Million Tons/Year)		1.64	6.9	----

[*] The values in Column 4 are scaled against the current market, but may take as much as 5 to 10 years for realization with maximum efforts.

[**] Value can be increased considerably with use of fly ash gas concrete in building construction.

[***] Has potential for accelerated future growth well beyond the proportions shown here.

[****] No appreciable increase.

[*****] Significant increases are possible through new developments such as ceramic products and mineral recovery.

Because of limited operational experience with the wet scrubbed process, data pertaining to modified fly ash properties and potential uses is limited. Based on the limited theoretical analyses performed during this study and those collected from researchers in the industry, it was concluded that there may be certain potential uses for the modified ash, but that research and development are required to establish any of them as being technically and economically feasible. The potential impact of modified ash on the total regular ash market cannot be estimated since the extent to which the wet limestone processes will be used is not known. Its potential impact would be best estimated in terms of what effect it would have as a replacement for the regular ash in a particular locality, and this can be done accurately only after technical and economic study, research, and development of the modified ash is made. Early indications are that technically, the modified ash may be able to substitute (with appropriate alterations) for the regular ash in road base construction and cement production, lightweight aggregate (accompanied by sulfur collection), fill material, autoclave products, and possibly gas concrete if the market exists. It does not appear to be a reasonable replacement in portland cement concrete without considerable beneficiation. New potential uses include gypsum products, pressure sintered products, new asphalt filler materials, sulfur production, and mineral extraction.

1.3.1 Fly Ash Unmodified

1.3.1.1 Specifications and Fly Ash Quality Assessment

All known specifications for fly ash used as a material for product manufacture or application, and for fly ash products were examined for the purpose of assessing the extent to which they inhibit the utilization of fly ash. It was determined that except for the specifications on fly ash as an admixture in portland cement concrete, specifications do not inhibit the use of fly ash. Detailed discussion on specifications can be found in Section 4.3.

There are individuals and organizations who, by combining the production or procurement of quality fly ash, appropriate concrete technology, and dissemination of the knowledge, have marketed fly ash readily within the limits of existing specifications (ASTM or Federal Bureau Specifications) or have written their own (e.g., TVA). The general fly ash community has not done this and therefore the use of fly ash concrete is not widespread. The lack of understanding of fly ash concrete by the general community, isolated cases of misuse of fly ash, and the dissemination of inaccurate or misleading information concerning fly ash (e.g., broadcast of the term "waste product," intolerable low early strength, bad color) has inhibited potential dealers, contractors, architects, and engineers. The power companies (with few exceptions) have not taken the initiative to improve the quality of fly ash or to maintain a consistent quality. Improvement in that area would undoubtedly relax the inhibitions to the use of fly ash by giving potential users the assurance of having a readily available supply of a quality grade of fly ash.

It is believed that a considerable portion of the fly ash produced today is usable as an admixture in portland cement concrete. Section 4.3 presents a comparative analysis of existing fly ash sampling data with existing specifications for fly ash as an admixture in portland cement concrete. Table 4-13 shows that approximately 60 percent of the fly ash is usable in concrete, with 6-percent loss on ignition (LOI) and 20 to 22-percent residue on 325-mesh sieve being the key considerations. A significant factor which could not be verified during this study was obtained from unofficial information. This information indicated that the 60-percent usability factor noted above could be increased to approximately 80 percent by using existing power plant personnel and equipment more efficiently through improved maintenance and operation of combustion and ash collection equipment. A well-recognized result of that would be an improvement in power production efficiency.

It is interesting to note in Table 4-13 the effect of a proposed change in ASTM Specification C-618 which would make acceptable approximately 78 percent of fly ash produced. Certain reservations to this are discussed in Section 4.3.3.6.

Because the specifications for fly ash as an admixture in concrete are numerous, conflicting, and irrelevant in many respects, recommendations are made that new specifications or procedures be written that will recognize properly proportioned fly ash concrete as a standard technology which relates various grades of fly ash to structural concrete usages, and includes design strength beyond 28-day cure. A procedure which avoids the current time-consuming process of specification writing, verification, and approval is advisable.

1.3.1.2 Concrete

Fly ash is used in portland cement concrete for the improved properties it imparts to the concrete. Among these improvements is pumpability, compressive strength, long-term strength, workability, finishability, and resistance to sulfates and alkali-aggregate reaction; it decreases the heat of hydration, drying shrinkage, particle segregation, bleeding, permeability, and leaching. These qualities are well-documented (see Section 4.2.1.1) and have been demonstrated repeatedly in actual practice. The net effect is a stronger and more durable product which requires less cost to put in place and finish. It is significant to note that for properly proportioned fly ash concrete, early strength, form removal periods, and curing requirements are not use-inhibitions.

Principal inhibitions to the use of fly ash in concrete are the lack of a dependable supply of usable quality ash, and the nonrecognition of the technological gains and potential improvements (see Section 1.3.1) which would allow the use of various qualities (or classes) of fly ash and greater than 28-day design strength criteria.

As noted earlier, a fly ash concrete technology (now practiced by only a few individuals in the concrete industry) which allows the use of more and coarser fly ash should be recognized and publicized through a new set of specifications or procedures, including the recognition of the long-term curing strength of fly ash concrete.

The choice of concrete cure time should be based on the economics involved with construction. Since the cost impact on materials by using fly ash is often small relative to the cost of placing and finishing the concrete, the design conditions should be dependent upon the requirements of construction. However, the state-of-the-art in concrete construction requires design compressive strengths of 28 days and does not include an optimal cure time in the total economics. A cure time of 28 days represents that point at which portland cement concrete will attain up to 90 percent of its ultimate strength and is considered representative of the true strength of the concrete. However, in concrete containing fly ash, 28-day cure times are arbitrary and meaningless since the strength tested at that time does not represent the ultimate strength of the concrete when fully cured, which occurs after 28 days. Using a 90-day cure, for example, allows more fly ash, less cement, provides higher strength, and affords advantages in pouring, pumping, and finishing. While the concept of 28-day design strengths largely dominates the concrete construction industry, there are few examples that can be cited in which structures under construction will experience their design loads in 28 days. Until the concrete construction industry becomes aware of the increased latitude in concrete mix design that is offered by a technology using fly ash in an effective, economical manner, an inhibition to the use of fly ash in concrete will persist. The architects, engineers, contractors, and concrete producers must be educated in this respect.

The continued development and acceptance of properly proportioned fly ash in concrete is likely to provide the basis for renewed interest in fly ash as a concrete ingredient. Intensive sales campaigns, although beneficial, have been effective only in local regions. When the users of concrete become fully aware of the range of advantages and properties that properly proportioned fly ash concrete offers, their reluctance to use fly ash in concrete should diminish and an increase in demand may be expected.

Significant deterrants to the massive use of fly ash in concrete, assuming the supply is made adequate (see Section 1.3.1) and the technology is improved, are the requirements for additional storage and handling equipment at the ready-mix plants, and hauling costs. A study of the economics of fly ash concrete related to the ready-mix operation was performed to determine if that is an inhibitory factor since the literature is weak in this respect. A detailed, comprehensive cost analysis could not be performed within the extent of this study because of: (a) the numerous, variable factors involved plus the variation in costs from region to region; (b) the use or nonuse of beneficiation of the fly ash, brokerage fees, and financial assistance to ready-mix dealers for new equipment; and (c) sliding costs related to local competition. The analysis was therefore limited to estimates of the more significant factors, i.e., costs of fly ash F.O.B. utility, cement, truck hauling, new equipment, and chemical admixtures. Strict conclusions cannot be drawn from this analysis because of the many cost variations involved for each case; however, indications are that (based on Table C-6 in Appendix C) a dealer can increase his profit before taxes by approximately 50 cents per cubic yard if high quality fly ash concrete is delivered within 10 miles of the fly ash source, or he can break-even at about 150 miles. On the other extreme, there is the possibility of a combination of circumstances, including the use of low-grade fly ash, which indicates that he will not be able to match portland cement air-entrained concrete on an equal production economics basis. In most cases, however, the dealer should be able to produce fly ash concrete to compete with portland cement concrete for haul distances of approximately 50 to 150 miles, depending on the many cost factors involved. Since the profit, before taxes, on portland cement concrete is in the range of $2 to $3 per cubic yard (according to various personal contacts), a potential increase of 20 to 50 cents per cubic yard would be appreciable to the dealer. If circumstances, as noted above, increase the cost to the dealer, that increase is generally small enough to be absorbed by the contractor who stands to benefit from the economic and technical advantages of using fly ash concrete.

In consideration of the utilization of "greater-than-28-day" design strengths described earlier, the production costs of fly ash concrete can be reduced rather dramatically. Using this technology where applicable, cost reductions can be attained for any type of concrete, and for some it can be well in excess of one dollar per cubic yard.

Barge or rail transport provides a less expensive means of hauling fly ash than truck, but is applicable to only certain peculiar geographic situations. It should be noted that the development and acceptance of a standardized fly ash concrete technology by the concrete industry would expand the market and bring a large percentage of the power companies into the supply market; consequently, any transportation inhibition would be significantly decreased in most of the eastern half of the country.

1.3.1.3 Mass Concrete and Concrete Products

Fly ash is used in much of the mass concrete construction in dams and spillways conducted by the U.S. Army Corps of Engineers and the Bureau of Reclamation. Specifications exist for this use and fly ash is proportioned accordingly, principally to lower the heat of hydration and also for its pumpability feature. Technically, a larger percentage of fly ash could be used in these structures; however, the present proportioning is adequate. With the bulk of this type of work being performed in the western United States where fly ash must be transported for long distances, its use is not a strong economic incentive. With new coal-burning power stations opening in the West, it is possible that fly ash may become more economically desirable. Usage may increase, but the small number of such projects make this potential use a small percentage of the national supply.

Concrete products such as building blocks, pipe and precast units represent a very attractive field for fly ash usage. Fly ash is used for this application and is well accepted; its principal inhibitions are the lack of guaranteed quality ash, and transportation cost limits. It was estimated that if this industry were exploited to its fullest extent, it would consume a maximum of 5 percent of fly ash production.

1.3.1.4 Lightweight Aggregate

The predicted high future demand for lightweight aggregate is based on dwindling supplies of natural aggregates plus the increasing recognition by architects and engineers of a future demand for large-scale usage of lightweight concrete. Present developments of fly ash lightweight aggregate production technology in the United States, Canada, and Germany have been reviewed. All are still in various phases of development and are attempting to solve technical problems of production. Lightweight fly ash aggregate in the U.S. is not yet considered to be an economically competitive product.

This is an infant industry, and solutions to its problems are being sought and incorporated in the process. It has been shown that a quality product can be manufactured. Whether the manufacturing process and market can be sufficiently developed to economically compete with other lightweight aggregates remains to be seen. A significant increase in the utilization of fly ash for this application appears possible, but cannot be expected in the near future.

1.3.1.5 Portland Cement Manufacturing

Fly ash lends itself economically to the production of portland cement only under certain special situations where the manufacturing plant cannot be located adjacent to the major raw material source or where possibly the required mineral deposits are located close to a utility. However, in most cases such special situations do not exist. This, coupled with the fact that there is no need for new cement plants since the present market demands considerably less than production capacity, indicates that the potential for utilizing fly ash in large sums for the manufacture of portland cement is relatively low.

1.3.1.6 Bricks

Although fly ash can be used technically for making bricks, there is no shortage of clay deposits for brick making. The principal sources of fly ash in the United States are all close to ample sources of natural raw materials for brick manufacturing. Whether the coincidence of a depleting source of natural raw materials, a dependable local source of high quality fly ash, and a knowledgeable entrepreneur will soon co-exist may determine whether fly ash will eventually find an application as an ingredient in brick. This is not expected on a wide scale. Additional factors indicating that this utilization potential will not materialize to any appreciable extent include: (a) fly ash brick manufacturing requires new handling equipment and production machinery, (b) fly ash bricks are not especially cheaper than ordinary bricks, and (c) the present United States brick production capacity exceeds demand.

1.3.1.7 Bituminous Filler

There are numerous uses for fly ash in bituminous products, however, its use as a mineral filler in asphalt concrete (black top) pavement is the major application for large tonnage usage. Low quality fly ash can be used, and current technology is sufficient. The competition to fly ash includes an array of low cost, abundant materials, all of which are adequate as a mineral filler. Although this is a good use for fly ash, particularly in consideration of the mileage of new asphalt roads (2 to 4 in. thick) or resurfacing of old roads (1 in. thick), the potential usage is not large, probably much less than one million tons per year. This limitation is caused by competition and is aggravated by the special problems of storage and handling.

1.3.1.8 Road Construction

Except for use as a mineral filler in asphalt, or occasional use as a structural land fill, road base course applications appear to be the only practical large-scale use for fly ash in road building. Although this application has an extremely large potential, supported by the facts that the technology is developed and a technical superiority over competing materials has been demonstrated, certain inhibitions are preventing a substantial growth of this application. It is not widely used in road contracts even though its cost is less than or equal to competing materials of equal strength for urban construction. Proven applications are classified as lime-pozzolan-aggregate base courses (pozzolan base), which involve patent rights. Factual data which would substantiate the inhibition of the use of this material because of royalty payments were not found; however, such an excuse has been given for nonuse on occasion. An example of competition which a pozzolan base course cannot meet is the use of a gravel or crushed rock base 6 in. thick under 2 to 4 in. of asphalt paving. Some municipalities, after allowing this form of construction, have later been faced with the continual problem of repair of a failing roadway.

The pozzolan base course is used mostly for urban applications. Portable mixers are not widely used, and hauling costs are often limited by the use of materials available at or near the construction site. However, the amount of paving urban roadways, subdivision streets, parking lots, and airports represents an extremely large market. Present usage appears to extend as far as 40 to 50 miles from the mixing plant. Almost any fly ash produced today is adequate for this application, and it can be stored outdoors during the winter months and, with minimal processing, can be used during the construction season.

The true inhibitions to the use of pozzolan bases is not apparent even after contact was made with over two dozen state highway departments. Most states are aware of its benefits but have chosen not to use it. The reasons given were almost always vague. The principal inhibition may be that most potential users have not had experience with it and are reluctant to make a change. A thorough, detailed marketing analysis of road construction would be required for the various regions of the country within range of potential pozzolan base course supplies to determine the justification and advisability of action by government road contracting agencies as regards the consumption of fly ash for this purpose.

1.3.1.11 Land Fill

Where structural land fill is required and hauling distances are short, fly ash can often be used more economically than other fill materials and can provide technical advantages. It is handled and hauled in a wet condition, thereby eliminating special handling provisions. Among these advantages are ease of handling and spreading, low compaction density, and shear strength that continues to increase with time (a consequence of pozzolanic reaction with residual lime content in the ash). Fly ash, when covered with soil, provides excellent drainage for vegetation. Also, any grade of fly ash is adequate and does not have to be stored, handled, or hauled in an enclosed and dry condition. However, the use of fly ash for land fill (excluding fly ash disposal) is not widely applied in this country. It has demonstrated its usefulness in the United States in embankments and abutment backing in highway construction, but it is not widely used for these purposes because of the availability of natural fill materials. Except for special circumstances such as extremely high fill embankments for roadways built over weak subsoils, or other cases where local fill materials are not available, little use of fly ash as a land fill is expected except for disposal purposes.

1.3.1.12 Mineral Wool

The use of fly ash as the raw material for mineral wool manufacture requires no deviation from the state-of-the-art commercial manufacture of mineral wool, and there appears to be no technical inhibitions to the use of fly ash in this application.

Inhibitions are apparently in the comparative economies of manufacture and in the likelihood of overcapacity in competition with mineral wool and fiberglass insulation materials. To date, a market position for fly ash mineral wool has not been found.

1.3.1.13 Gas Concrete

Gas concrete, a porous concrete building material which is approximately one-fourth to one-third the density of ordinary concrete, utilizes fly ash up to 80 percent of the solid constituent weight. It is made in patented European processes and is widely used in many foreign countries but not in the United States.

European utilization of gas concrete has proven it to be a highly desirable form of building material from the standpoint of construction economy and structural qualities. It is used in at least 20 countries; for example, it is used on a wide scale in Denmark; in West Germany, gas concrete is used in the construction of 80 percent of all new factory buildings, while in Sweden such use approaches 100 percent. Additionally, in the Philippine Islands it is now being used for the construction of low-cost housing projects, and in England, it is expected that in 1971, one million tons of fly ash will be consumed in gas concrete. Since fly ash improves the quality of gas concrete, reduces capital and production costs, and is available in abundance in urban areas, it could conceivably find a large market throughout the United States as a constituent of gas concrete. Additionally, fly ash used for this purpose does not have to be fine quality and it can be hauled and applied in a wet state, thereby allowing simplicity of handling.

The future of gas concrete in this country is not readily assessable. As a new industry, it would have to compete with numerous well-established building techniques using conventional materials. To establish fly ash concrete as a building construction material on a wide scale would require substantial technical and economic surveys, coupled with the dissemination of the technology. Such a program is recommended.

1.3.1.14 Miscellaneous Uses and Potential New Uses

Other uses such as in foundries, grouting, pipe coating, oil well cementing, etc., are considered to have a low potential for the consumption of large quantities of fly ash. A large potential exists for possible new uses such as sewage filtration/soil supplement applications, ceramics and mineral recovery. None of these has been developed.

1.3.2 Limestone-Modified Fly Ash

The wet collected limestone-modified fly ash differs considerably, both chemically and physically, from the regular ash and as such does not lend itself to the direct substitution for the regular ash as it is used today. Additionally, the chemical and physical properties of the modified ash vary to a large degree based upon the sulfur content of the coal burned and the percentage of coal burned which becomes fly ash.

There are numerous potential uses for the modified ash, some the same as for the regular ash and some not yet developed. Programs of research and development are necessary for the determination of the technical and economic feasibility of utilization schemes for this material. This is discussed in some detail in Section 5. Specific problems confronted in seeking these uses include: (a) variable quality of the ash, (b) it is wet collected, therefore subject to concreting; (c) it contains sulfur which would be released during some processes involving heating the raw materials; (d) is pozzolanic properties are decreased compared to the regular ash; (e) the volume of fly ash is greatly increased compared to regular ash; and (f) toxic trace elements may be released with contained soluble sulfites and sulfates. On the plus side, the ash does contain: (1) pozzolanic properties; (2) unreacted lime; and (3) appreciable amounts of gypsum.

General areas of potential technical utilization include autoclave products, structural or land fill, bituminous filler, pozzolanic materials, cement manufacture, pressure sintered products, gypsum products, and mineral recovery. Immediately promising areas are autoclave products (sulfur would not be released), gypsum products (it contains large amounts of gypsum), road base course material (it contains lime and pozzolanic properties and the potential market is large), and sulfur recovery (although the economics are not promising, it could supplement a sintering process). Characterization and utilization research are recommended.

Since the modified ash cannot replace regular ash in its utilization, it can be said that its immediate impact on the regular ash market would be negative. It is possible, however, that processes can be developed that would make it usable by the time its production quantities become appreciable.

1.4 SUMMARY OF RECOMMENDATIONS

1.4.1 Regular Fly Ash

The existing inhibitions to the utilization of regular fly ash are of such magnitude that only a small percentage of the ash produced today is utilized. It is believed that the inhibitions will continue to prevent an appreciable growth of the fly ash market if appropriate research, development, and survey programs are not carried out. Properly conducted, these programs have the potential for removing inhibitions such that all or a major portion of the fly ash could be profitably used.

The major areas of concern for new efforts are structural concrete, road base course materials, and new products such as gas concrete, ceramics, and mineral recovery. It is felt that sufficient effort is already being applied to the advancement of the fly ash lightweight aggregate technology. Additionally, an effort should be directed toward the extended use of fly ash as a mine void fill, particularly since it could serve as an interim measure until the efforts requiring more lead time are completed and put into practice.

The recommendations are:

1. A new set of specifications or a handbook should be expeditiously developed for the use of fly ash in portland cement concrete which would provide a standard utilization to produce predictable results. This would include the application of various grades of fly ash (pertinent parameters such as residual carbon, fineness, and pozzolanic activity) to concrete usage and encompass cure times beyond 28 days. This could be modeled after TVA specifications G-2 and G-30 (Refs. F-80 and F-81) to expedite the process. A testing program will be required to provide statistical data to support this program.

2. A marketing survey should be conducted for various regions within the fly ash supply areas to determine the economic feasibility of fly ash gas concrete in various forms of building construction in the United States.
3. A technical and marketing survey should be conducted in various regions of fly ash producing areas to determine the justification for an advisability of action by government road contracting agencies as regards the use of fly ash in the base course section of federal, state, and local paving program contracts.
4. Research should be performed for mineral recovery from fly ash.
5. A survey study should be conducted to evaluate the net economic effects of coal-washing or gasification on the fly ash market and on the cost of ash disposal.
6. A technical and economic survey should be conducted related to land reclamation and to the remote filling of mine voids for control of mine subsidence and fires. This would include the economics of fly ash usage and land reclamation values; in addition, it would include the effects of fly ash on ground waters. The use of empty coal cars or a fly ash slurry should be considered for transportation.
7. Research and development should be conducted to develop or improve uses for fly ash such as ceramic products, optimized fly ash gas concrete, and those uses not yet identified.
8. Fundamental research should be conducted that can identify the intrinsic characteristics and properties of fly ash to provide the basis for subsequent research into new uses of fly ash. This has been performed in part at various organizations, but results of complete characterization are not published.

1.4.2 Wet-Collected Limestone-Modified Fly Ash

The determination of the potential use of the modified ash is dependent upon research and development programs and marketing surveys to determine an understanding of the potential marketability of developed products in terms of public acceptance and ability to compete with other products, including those produced from regular fly ash. The following programs are recommended:

1. The most critical research to be conducted on wet-limestone-modified ash is the fundamental characterization of its chemical and physical properties to provide the basis for subsequent utilization and toxicology research described in Recommendations 2, 3, 4, and 5, as applicable.
2. Research and development programs should be conducted on potential mass uses of modified fly ash to include filler materials, autoclave products, pozzolanic materials, pressure sintered products, and gypsum products (specific products are discussed in Section 5). These programs should be broad enough to allow the possible emergence of uses not yet identified. Additionally, these programs should consider the mass usage of modified ash *in situ* and beneficiated in processes in which sulfur is not released and in processes in which sulfur is released and recovered.
3. Research should be conducted on the recovery of mineral ore from the modified fly ash.
4. Research should be conducted to determine the physical state of toxic elements within the modified fly ash and the source of these elements (coal ash or limestone), the role of wet collection in the prevention of mass contamination via particulate and gaseous effluents, and the potential hazards that may exist, particularly through leaching, in the disposal and utilization of the ash.
5. Surveys should be conducted to determine the potential for marketing recovered sulfur and products to be developed for the use of modified fly ash. Consideration should also be given to the development of products which are already partially developed; e.g., mineral aggregate and road base course materials.
6. An economics survey should be made of the phase of electric power production involving the effects of fuel preparation and delivery, pollutant removal, residue disposal and product credits. Examples of trade-offs which should be made, include: (a) scrubbing of fly ash and gases resulting from the combustion of untreated coal, (b) scrubbing of fly ash and gases resulting from the combustion of cleaned coal, (c) gasification of coal, and (d) liquefaction of coal.

SECTION 2

INTRODUCTION

2.1 PURPOSE OF STUDY

The Office of Air Programs of the Environmental Protection Agency, in its association with the development of schemes for the removal of sulfur gases from the stacks of coal-burning power companies, has expressed an interest in the present and potential utilization of fly ash as well as any impact on that utilization caused by modification of the fly ash during the sulfur removal process. The fly ash modifications to which this study was directed in part is caused by the wet scrubbing of the fly ash and stack gases. Presently, only a small percentage of the fly ash produced is marketed; no modified ash is marketed at all. The non-marketing of the modified ash is due to the fact that the limestone modification systems are still being developed; therefore, the modified ash is produced in relatively small amounts of varying quality in only a few locations. Additionally, uses for modified ash have not been developed. Hence, this study has concentrated on forming an understanding of the present utilization of the regular (unmodified) fly ash, inhibitions to its use, and means of removing those inhibitions. To that was added a survey of the qualities of the modified ash, potential utilizations, and recommendations for development programs.

2.2 SIGNIFICANT FACTORS PERTAINING TO FLY ASH UTILIZATION

2.2.1 Regular Fly Ash

Fly ash is used principally as an admixture in applications such as concrete, concrete products, and road base materials, providing qualities or characteristics superior to those products not using fly ash. Additionally, it has excellent compaction qualities and is amenable to sintering and autoclave processes for manufacturing certain constructional materials. In spite of the many advantages, the use of fly ash is limited[*], principally because (a) it is a by-product of power production and consequently is generally produced with little or no regard for quality or consistency, (b) it is difficult to handle, (c) utilization technology has not reached a level near its potential and some major technological advancements have not been widespread, and (d) previous misuse, incorrect criticisms, and fears of risk have marred its reputation. Through the research and perseverence of certain individuals in The Chicago Fly Ash Company, the TVA, and the G. and W.H. Corson Company in Plymouth Meeting, Pennsylvania, as well as numerous others in both the United States and foreign countries, fly ash utilization technologies have been developed and practiced which prove the value of this material and discount false impressions held by many individuals both in and out of the fly ash business. Additionally, a few power companies have demonstrated that quality fly ash can be produced consistently (concurrently improving the efficiency of power production) and some have participated in the development of fly ash products or applications and are using fly ash in their own construction. Still other individuals have developed methods and procedures for beneficiating fly ash for various utilizations, and numerous universities and government agencies have advanced the utilization technology through research activities. To these activities has been added the National Ash Association, which was founded in 1968 for the purpose of promoting the sale and use of all types of coal ash. This Association, consisting of membership from the power utilities, coal companies, researchers and consultants, collects and distributes all forms of ash information, publishes an ash newsletter, writes and presents relevant ash utilization papers, sponsors technical and marketing meetings, coordinates the American ash utilization community with foreign ash production and utilization groups, and provides information to those individuals or groups interested in ash utilization.

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[*] An exception is the Chicago area where a combination of available high quality fly ash, technology, and sales promotion accounts for utilization of approximately 75 percent of the fly ash produced by Commonwealth Edison.

With all of these efforts, the national fly ash market is generally inhibited and is not experiencing an appreciable growth. In the interest of utilizing fly ash, the need for identifying the inhibitions and determining means of removing them is apparent.

2.2.2 Wet-Collected Limestone-Modified Fly Ash

The modified fly ash is quite different from the regular ash, so much so that it could easily be considered a new material. Except possibly for use as a filler material, it cannot be substituted for the regular ash in consideration of today's technology without extensive research and development. As a filler, it would require some development work to satisfy all considerations of use and performance. Study and research programs that have been performed to date indicate that there are numerous potential uses for the modified ash. The major portion of research has been performed by Combustion Engineering, Inc., of Windsor, Connecticut, and by the Coal Research Bureau of West Virginia University. These efforts have identified many characteristics of the material and potential uses, but research is not complete, and developments are minimal or nonexistent. Some developments of a proprietary nature, such as at the Corson Company, are progressing and have been reported in technical papers (Ref. D-1).

Modified ash, therefore, is appreciably different from regular ash, both chemically and physically; it will be produced in much larger quantities per pound of coal burned than regular ash and its utilization potential can only be determined through extensive research and development programs. Its marketability, once products are developed, will resemble that of the regular ash in many respects.

2.3 ORGANIZATION OF STUDY

This study was performed in the following four steps:

1. Literature survey
2. Contacts with individuals and organizations
3. Inhibitions analysis
4. Determination of necessary actions to eliminate inhibitions

The literature survey was conducted to provide a factual background for the study and to aid planning of continuing activities. The contacts with the fly ash community provided considerable actual practice data and guidance for the study. The inhibitions analysis was based on the information obtained from the literature and personal contacts. With the exception of some minimal efforts on economics, most of this analysis effort consisted of obtaining pertinent factual data, placing it in proper perspective, making rational comparisons and follow-up inquiries, and forming rational judgments. The recommendations for removing use-inhibitions are considered the most feasible and rational of all possibilities determined by the study members and those suggested by members of the industry. Many suggestions were not used because it was believed that they involved programs which either were more elaborate than necessary (e.g., "form a national fly ash research center"), or were considered inadequate for wide scale mass utilization (e.g., "depend on promotion and salesmanship"); or were based on nondedication to the utilization of fly ash (e.g., "bury it").

2.4 SCOPE OF EFFORT

It is important to the understanding of this study to note that it consists principally of a compilation of facts as they appear in the industry today, and that it was not a research program to test or develop materials or products. Neither is it an attempt to provide information on how to produce or construct anything such as concrete, roads, or aggregate. Its purpose is to provide an insight as much as possible into the total fly ash production and utilization picture, to make rational estimates of the nature of situations or problems, and to make recommendations for solutions. It is realized that the "total picture" could not be obtained within the scope of this study, in light of the vast number of individuals involved, conflicting points of concern or interest, the many different technologies involved, varying geographic considerations and limitation, and ever-changing economic conditions. It is believed, however, that sufficient coverage has been made to provide rational statements of the situation and recommendations considered necessary to appreciably improve the fly ash market.

SECTION 3

LITERATURE SURVEY AND PERSONAL CONTACTS

3.1 LITERATURE SURVEY

Appropriate literature pertinent to this study has been collected, surveyed, and compiled into a fly ash library. A survey of this literature was performed merely to obtain information; therefore, literature reviews are not a part of this report. A bibliography is provided in Appendix A. It is subdivided into the following sections: Fly Ash Production, Fly Ash Properties, Fly Ash Utilization, Limestone-Modified Fly Ash Technology, Foreign Technology, Specifications and Regulations, Sulfur Dioxide Control, and Miscellaneous. Because there is some overlap in the indexing system, cross-referencing is provided as necessary. All literature references within the body of the report are made to the documents listed in Appendix A.

3.2 PERSONAL CONTACTS

A listing of all contacts made during this program is given in Appendix B. That appendix is subdivided as follows: Fly Ash Production, Beneficiation, and Marketing; Fly Ash Utilization, Specifications, and Technology; and Limestone-Modified Fly Ash. Because of the overlap of interests, some individuals are listed more than once. Approximately 65 of these were visited personally and the remainder were contacted by letter or telephone. The cooperation of all of these individuals is commendable, and the time and data provided is appreciated. Sincerest apologies are offered to those who participated but whose names may have inadvertently been omitted from this list.

SECTION 4

FLY ASH SURVEY

4.1 FLY ASH PRODUCTION

Since this study considers fly ash as the particulate residue that results from the burning of pulverized coal to generate electric power, the quantity of fly ash produced necessarily becomes a function of the energy requirements from the combustion of coal. The growth in demand for electric power in recent years has been phenomenal. According to Ref. H-15, the total energy consumption in the United States per capita has increased almost 300 percent from 2500 kwhr in 1950, to 7150 kwhr in 1970. Also, from statistics collected in Ref. A-19, the United States presently consumes over one-third of the world's 4.2 trillion kwhr of electricity with coal-burning power plants providing almost one-half of this country's yield. Of the total amount of coal consumed for all purposes, the proportionate quantity utilized by the electric power generating companies has shown a steady increase since 1945, and as illustrated in Fig. 4-1, this currently represents 56 percent of the total United States coal consumption.

Although it is recognized that a saturation point must be eventually reached, the present rate of expansion in electric power is expected to continue to the year 2000 (Ref. H-15). The coal industries participation in this expansion appears to be well assured despite the increased amount of power expected to be produced by nuclear and petroleum fuels. With the United States possessing one-third of the earth's estimated 5.1 trillion tons of coal reserves (Ref. A-19), this country's coal consumption is expected to increase rapidly year by year due principally to the anticipated vast increase in electric power generation. The increased power demands during this period will also, in all probability, result in the necessity for increased consumption of lower quality coals.

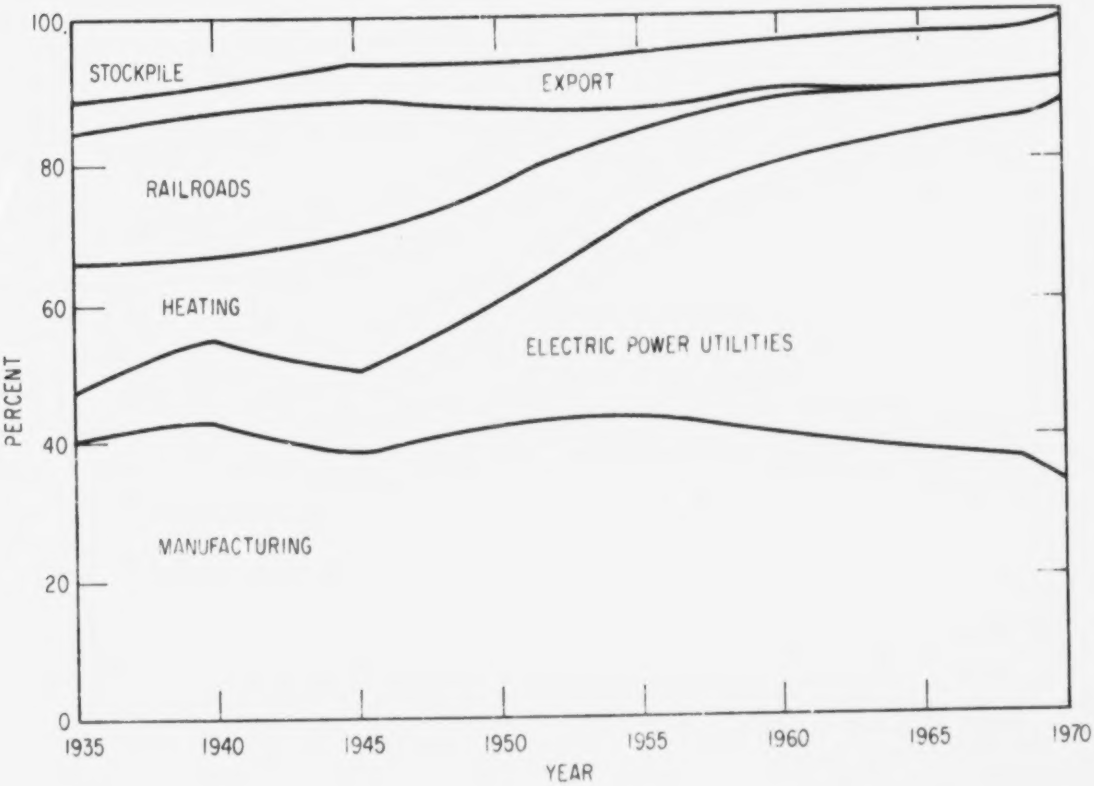

Fig. 4-1. United States Coal Consumption

The past, present, and projected consumption of coal and fly ash production by the electric utilities in the United States is shown in Fig. 4-2. The basic data for these curves were obtained from Brackett (A-2 and A-5) and the Edison Electric Institute. The requirements for power plant energy for the combustion of coal was 300 million tons in 1970, with expected increases to 400 million tons per year by 1975, and 480 million tons per year by 1980. In addition, this figure shows the actual fly ash production for the years 1956 through 1970, with the projected production based on coal consumption estimates. The abrupt increase in the rate of fly ash production between 1969 and 1970 can be attributed to the energy crises that prevailed during

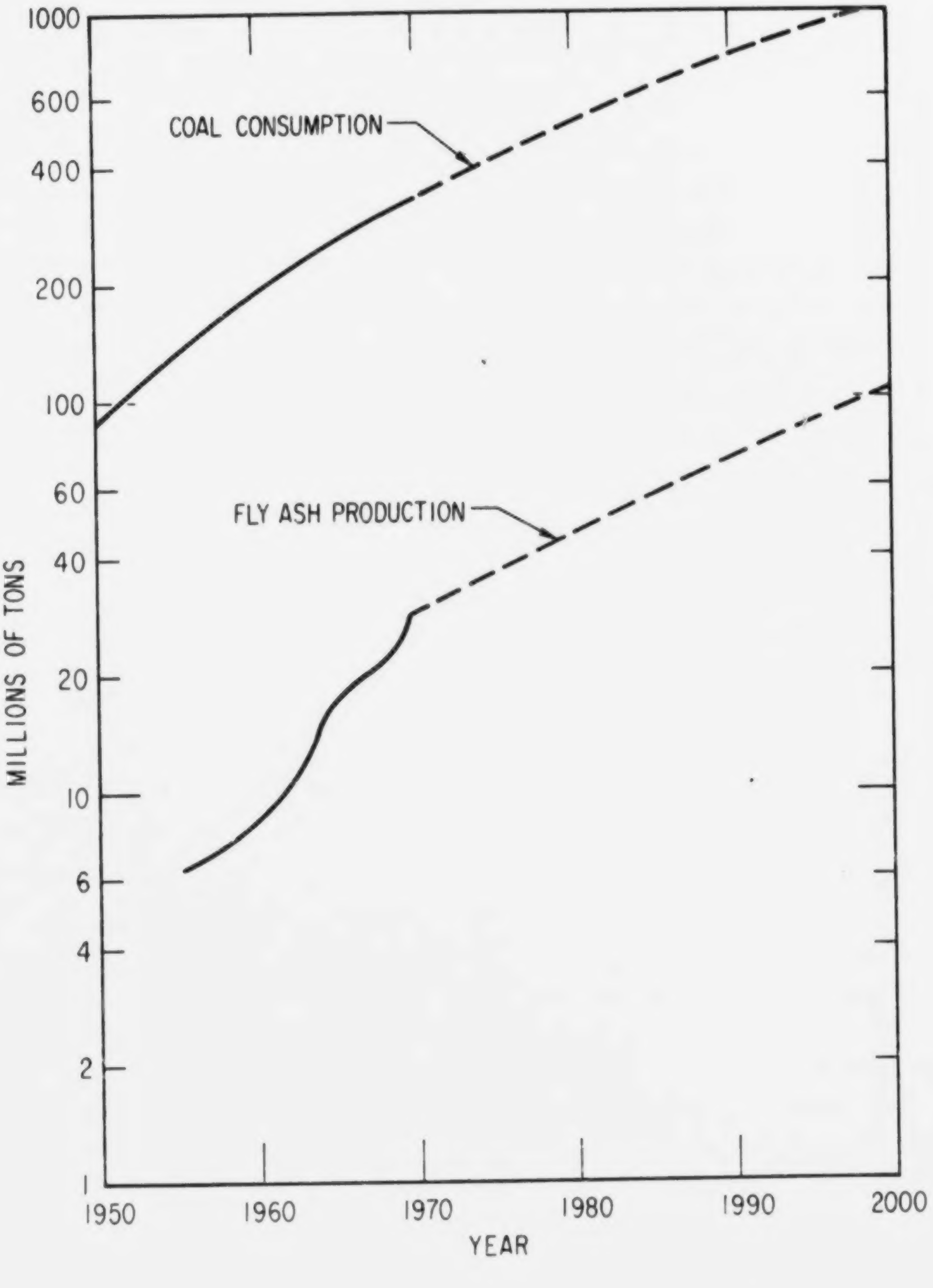

Fig. 4-2. Coal Consumption and Fly Ash Production

this period which compelled power plants to burn a lower quality of coal than had been previously acceptable. The utilities affected by these crises reported increases in fly ash production in the range of 25 to 50 percent. As stricter standards for particulate control devices are imposed on the coal burning utilities, the amount of fly ash removed from stack emissions will also result in significant increase.

4.1.1 Fly Ash Geographic Distribution and Availability

As might be expected, a major factor in the marketing of fly ash is distribution and availability. The availability of fly ash is greatest in those large urban or metropolitan areas presently served by electric utilities using coal to generate power. Figure 4-3 indicates those states and metropolitan areas where the largest coal-burning utilities (exceeding 400,000 tons per year) are located. The Middle Atlantic area, which includes New York, New Jersey, and Pennsylvania, and the East North Central area, which includes Illinois, Indiana, Michigan, Ohio and Wisconsin, consume the largest amounts of coal in the generation of electrical energy (Ref. A-2). These are followed in order by the South Atlantic, East South Central, West North Central, New England and Mountain areas.

Although the large utilities in the Middle Atlantic and East North Central and East South Central areas are in rather close proximity and therefore afford fly ash availability, large areas still exist where fly ash is totally unavailable. As can be seen in Fig. 4-3, very little fly ash is available west of the Mississippi River, in the New England area, and in parts of the South. As a further illustration of the concentration of fly ash availability, data from the 1970 Keystone Coal Industry Manual were used to develop the curves presented in Fig. 4-4. This figure indicates that of the 489 power plants in the United States that burn coal, only 195 or about 40 percent consume over 400,000 tons of coal per year. However, these 195 power plants supply approximately 90 percent of the total quantity of fly ash produced.

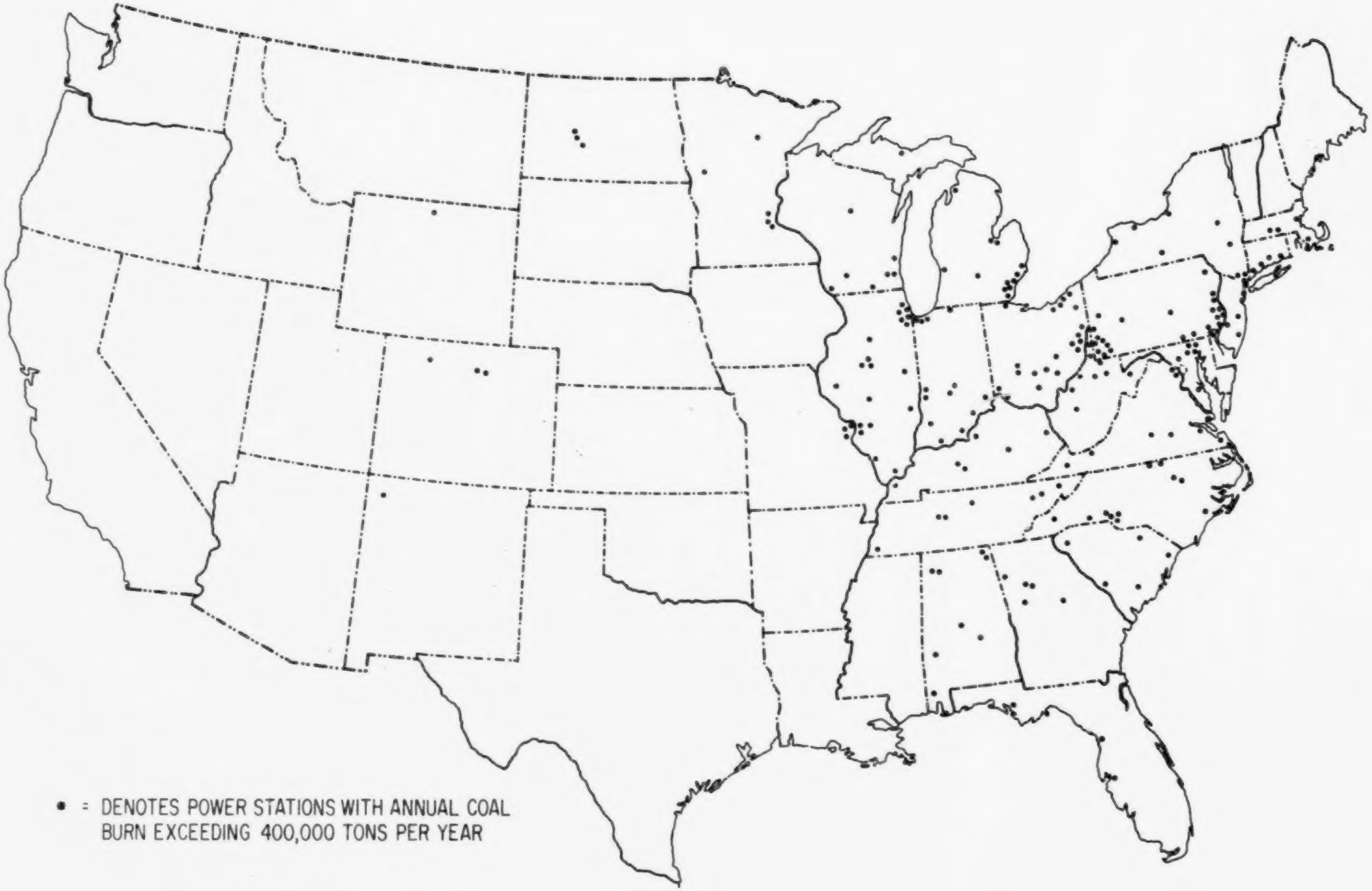
● = DENOTES POWER STATIONS WITH ANNUAL COAL BURN EXCEEDING 400,000 TONS PER YEAR

Fig. 4-3. Power Stations

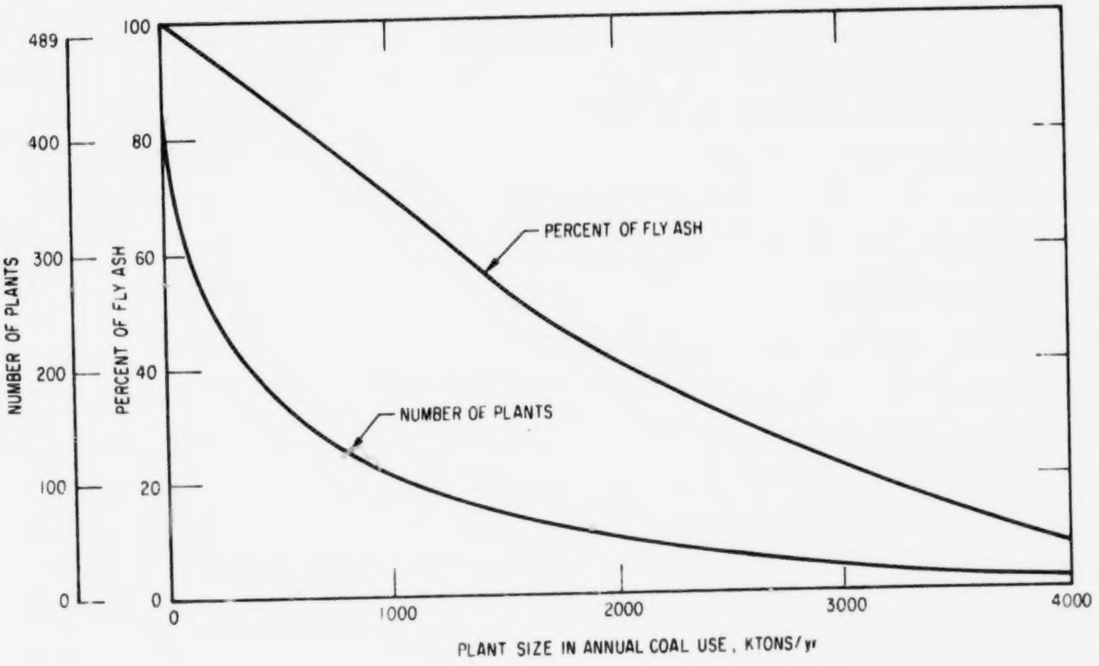

Fig. 4-4. National Fly Ash Production by Plant Size (Developed from Use Data in 1970 Keystone Coal Industry Manual)

4.1.2 Fly Ash Disposal Costs

The costs presently associated with the dumping or disposal of power plant fly ash in settling ponds or land fill areas, at the current production rate of 26.5 million tons per year, varies from as low as $0.50 per ton to as high as $2.00 per ton. With new regulations prohibiting the dumping of fly ash, fewer available disposal sites in the metropolitan and urban areas, and rising land costs, fly ash disposal costs are continuing to rise. From Fig. 4-2, it is estimated that 40 million tons of fly ash will be produced in 1975. At this rate, a conservative estimate of the average disposal cost of $1.00 per ton will amount to approximately 40 million dollars per year by 1975.

4.1.3 Freight Rates Versus Shipping Distances

Fly ash is in direct competition with many highly competitive bulk products which are basically low in unit price. As such, quality fly ash must be delivered to the sites for use at a sufficiently low price to insure that it is competitive. Therefore, freight rates become a major factor affecting the economic availability of fly ash for utilization purposes.

The extreme fineness and easy flowability of fly ash necessitates that it be shipped in air tight containers for many uses. In addition to shipping rates, the mode of transportation will depend on the location of the power plant and the site at which the fly ash is to be used. Currently, various modes, including truck, rail, and barge, are used in transportation.

Despite the higher shipping rates, the most common mode of transporting fly ash is by truck. Usually this mode is dictated by the relative locations of the fly ash source and the plant where it is to be used. A truck can normally transport 20 to 30 tons of fly ash per trip at a cost of $0.06 per ton/mile. For short haul distances, local shipping charges include a $1.00 loading and $1.00 unloading fee per ton. These costs were found to be quite uniform throughout the United States.

In transporting fly ash by rail, each car, containing two hoppers, can accommodate 55 to 60 tons. Except for a few special cases, the rate for transporting fly ash by rail is about $0.02 per ton/mile with an additional fee for shaking the car to complete the unloading. In some isolated cases, the rate for rail transportation was found to be as low as $0.01 per ton/mile.

The shipment of fly ash by barge requires that both the source and user be conveniently located to connecting waterways. Although barge shipping rates are relatively low, the necessity of transloading to and from the barge by truck or special conveying equipment results in this mode of transportation becoming competitively economical only for long (greater than 200 miles) distances. A barge can haul 1500 tons of fly ash over long distances at an approximate average of one-half cent per ton/mile. Also, because of the fineness and flowability characteristics, provision for covering fly ash will be an added requirement in transporting by barge.

4.1.4 Fly Ash Quality and F.O.B. Utility Costs

In order for fly ash to gain acceptance by potential users, it must not only be available economically, but at a uniform quality as well. The physical properties and chemical composition of fly ash produced by each coal-burning electric utility is dependent upon the characteristics of the coal that is used as fuel, the type of equipment employed, and the manner in which it is operated and maintained. Since these characteristics vary from plant to plant, it is not unexpected that fly ash properties vary from source to source. In addition, fly ash collected at any one source will change as the demand on the power plant varies from base to peak loading conditions and as conditions within the producing plant change. These considerations, as well as the fact that coal-burning electric utilities are primarily concerned with the production and sale of electric power, contribute to the difficulty in producing a fly ash of uniform quality. Added to this is the further obstacle that each product with fly ash utilization potential has individual quality requirements.

As indicated in Section 4.3, specifications have been written for the use of fly ash in concrete and concrete products. From a technical standpoint, these specifications permit fly ash with a carbon content of 6 to 12 percent. The manufacture of lightweight aggregate from fly ash or blended ash requires a consistent carbon content of between 4 to 6 percent, although fly ash used as a bituminous filler can tolerate carbon contents as high as 12 percent, and in road base courses, 15 percent. In addition, the fineness of fly ash to be used in most concrete mixtures requires that 78 to 90 percent of it pass through a 325 mesh sieve, whereas others allow as little as 68 percent to pass; and, for bituminous products, 75 to 80 percent passing a 200 mesh sieve is adequate. High Fe_2O_3 is undesirable in lightweight aggregate from a weight standpoint. It has an effect on concrete color, but much less than that of carbon (Ref. B-18). Although uniformity is a major requirement for all users of fly ash, it can be seen that the definition of quality will vary depending on the use or product to which it is being applied.

In order to market an acceptable product, some utilities have incorporated additional equipment, operating procedures, and controls to assure the production of a uniform quality fly ash. These measures and controls include: the washing and/or blending of coal to reduce the amount of ash or aid fly ash chemical consistency; frequent maintenance and calibration of coal pulverizers for consistent fineness; maintenance of high combustion efficiency in boilers to limit carbon content; and maintenance of fly ash collector efficiency within design limits to attain a fineness consistency. The latter does not appear to be technically feasible for either older plants and/or those plants frequently operating at peak loading conditions. Of the newer base-loaded plants, only a few have selected these approaches to produce fly ash of marketable quality.

Two unique operations exist in which the fly ash is beneficiated. In one, the Dayton Fly Ash Company in their Atlanta, Dayton, Pittsburgh, Terre Haute, and Wilsonville plants, pass the ash through mechanical air classifiers which reduce the 325 mesh residue to about 5 percent. This allows the fly ash company to meet its present supply needs without depending on the power company for high quality ash, but at the expense of the classification process.

In the other operation, a somewhat different approach to beneficiation has been developed by Enercon, Ltd., of Hamilton, Ontario. This company, in conjunction with the Stirling Sintering Company of Pittsburgh, has designed and built a modern, integrated facility adjacent to a power plant for the purpose of processing fly ash for total utilization (Ref. C-30). When fully operational, the plant will separate as-received fly ash into (a) a very fine fraction for use as a pozzolan, (b) an iron oxide concentrate, (c) a carbon fraction, and (d) inter-feed fraction for use in making lightweight aggregate for concrete.

At the time of this writing, the aggregate operation is not yet operational. Moreover, the value of the iron concentrate is less than the cost of separating it but is justified on the basis that iron removal upgrades the other fractions.

The profitability of the Enercon plant has not yet been demonstrated. However, it appears that the total utilization concept has considerable merit, particularly if excellent quality pozzolan and aggregate feed result from the operation.

The largest volume of fly ash is currently marketed by brokers that either process fly ash produced by the utilities and/or have the capability to selectively choose from numerous power plants that under known operating conditions will result in a specific quality of fly ash for a particular market.

Regardless of the process that is used in supplying a user with uniform fly ash that meets a particular product quality specification, the F.O.B. cost of quality fly ash at the source was found to vary between $3.50 and $4.50 per ton. Where the ash is marketed directly by the utilities, lower F.O.B. charges generally prevail.

4.2 UTILIZATION AND ECONOMICS

As indicated in Section 4.1, the continual increase in demand for electrical power in this country with the related increase in the quantity of coal burned yearly has resulted in the accumulation of fly ash at a remarkable rate. Alternatives for disposing of this accumulating by-product of power generation have become more and more restrictive as public and governmental pressure increases for better control of environmental pollution. Confronted with new regulations containing further prohibitions on the dumping of fly ash, this traditional disposal method has become less and less satisfactory with fewer disposal sites available in urban areas and disposal costs, already in excess of $2.00 per ton in some areas, continuing to climb. In addition, current considerations governing the choice between nuclear and fossil-fueled power plants include the economics associated with the disposal of the by-products of the combustion process. As a result, concentrated efforts to attain a feasible solution to this ever-increasing problem have been directed to the search for and development of applications in which fly ash can be utilized.

The efforts to find markets for fly ash have resulted in the development of numerous uses. On the basis of technical feasibility many of these uses can accommodate only small amounts of fly ash whereas others could account for the use of appreciable quantities. Currently, fly ash in this country is utilized in the manufacture of cement, concrete, and concrete products, land reclamation and construction fill, road base and soil stabilization, lightweight aggregate, and mineral filler for asphalt pavement. Miscellaneous uses for fly ash include grouting, oil well cementing, mine fire and subsidence control, pipe coating, sewage plant treatment and foundry filters, and manufactured products. The Fuel and Ash Subcommittee of the Prime Movers Committee of the Edison Electric Institute conducts a survey each year to obtain details of the annual production and utilization of fly ash from the coal-burning electric utility plants. From the latest survey results, the quantity of fly ash used in each major category during 1970 is presented in Table 4-1. These results indicate that the properties of fly ash are commercially useful and utilization varies greatly with the type of application.

Figure 4-5 illustrates the trend of fly ash production and utilization in the United States during the past 15 years. Although the utilization of fly ash advanced steadily from the early 1960's to 1968, the past few years have experienced a leveling off and even a slight decline while the rate of fly ash production has increased beyond expectations due to the recent energy crises.

The foregoing data indicate that although numerous uses of fly ash have been developed and are currently available, utilization still remains at less than seven percent of the total production tonnage. In order to assess the prospects for possible further growth in fly ash utilization, the high volume use potentials were investigated on the basis of economic and technical considerations. Table 4-2 lists high-volume fly ash uses which were selected on the basis of a United States total theoretical technically feasible application in excess of a million tons per year based on current fly ash production. These were selected on the basis that only in the application where there is the potential for mass marketing could a significant increase in the utilization of fly ash be realized. New uses or developments could, of course, increase this list. It is recognized that the potentials are overly optimistic in view of the varying degrees of economics, technology, and fly ash accessibility throughout the United States; however, for mass utilization to become possible, fly ash must be capable of being marketed as a quality product over large areas at sufficiently low prices to be competitive with low-cost bulk products such as sand, gravel, clay, and shale.

Table 4-1. 1970 Fly Ash Utilization

	Tons
Total Fly Ash Collected	26,538,019
Total Fly Ash Utilized	1,631,009[*]
Partial replacement for cement in concrete	536,320
Fill material for roads	320,304
Lightweight aggregate	207,019
Raw material for Portland cement	158,484
Filler in bituminous products	131,270
Base stabilizer for roads, parking areas, etc.	111,309
Grouting	75,872
Control of mine fires	14,000
Oil and gas well conditioning agent	7,523
Foundries - manufactured products	4,260
Pipe coating	1,603
Miscellaneous	64,044

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[*] Not included is the reported fly ash removed from plant sites at no cost to utility but not covered in use categories shown: 526,347 tons. Unofficial estimates by the Edison Electric Institute are that some of this tonnage may be dumped at no cost to the utility, some may be used, and some may be stored for later use.

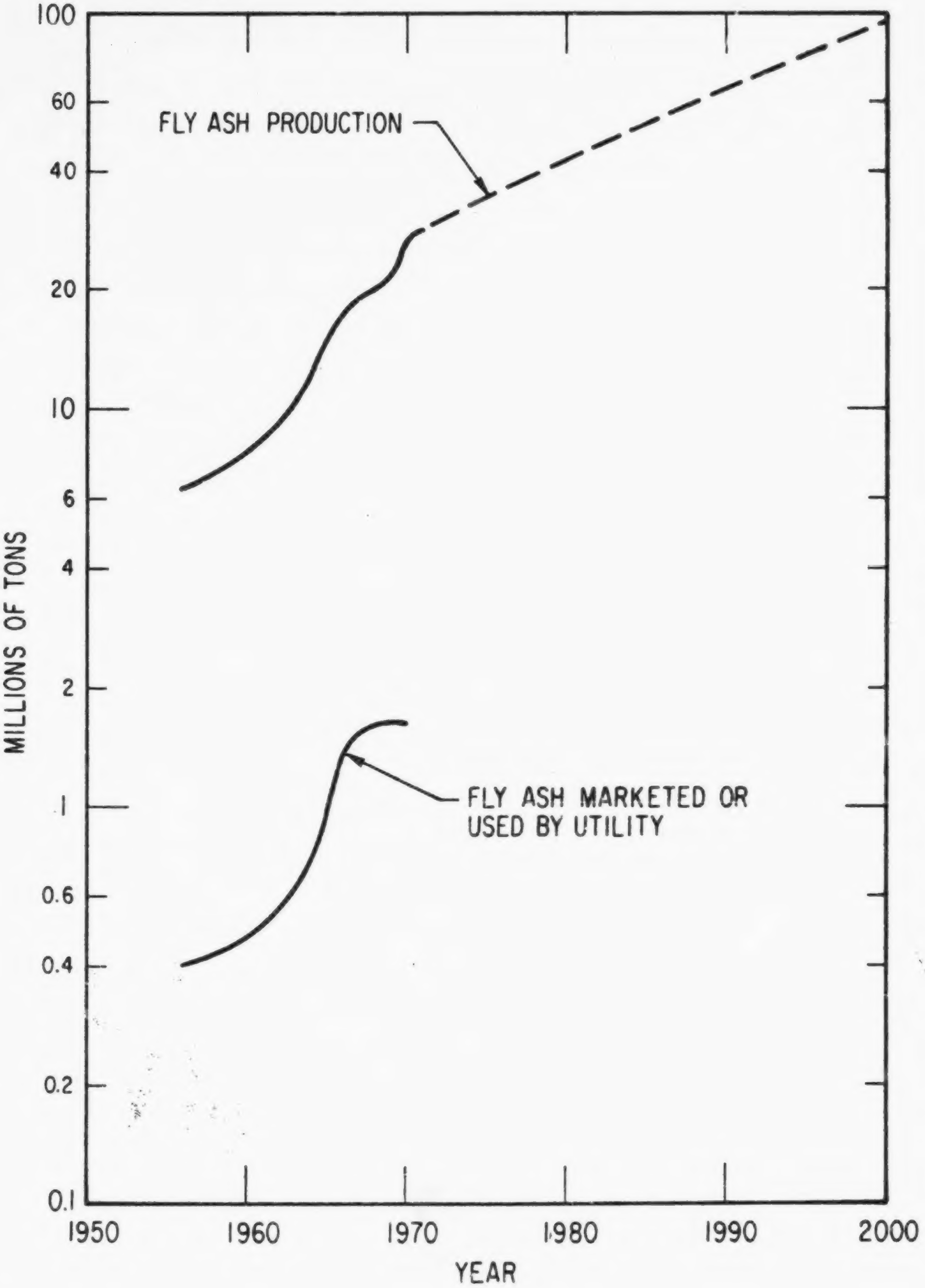

Fig. 4-5. Fly Ash Production and Utilization

Table 4-2. Potential Fly Ash Utilization

Application	Amount of Fly Ash (Tons/Year)
Fly Ash Concrete	10-15,000,000 (C95, C55, C120, C87)
Lightweight Aggregate	13,000,000 (B15, C10, C31)
Raw Material for Cement	13,000,000 (C11)
Bricks	10,000,000 (C87, C99, C53)
Filler in Bituminous Products	1-2,000,000 (A9, B15, C49)
Base Stabilizer and Fill for Roads	> Annual Production (C87)
Agriculture and Land Reclamation	> Annual Production (C19, B15)
Control of Mine Subsidence and Fires	> 1,000,000 (C51, C133)

The following paragraphs treat each of the selected uses of fly ash separately. In view of the fact that concrete appeared to offer one of the greatest technical and economic advantages for the use of fly ash, and has a high potential for near-term utilization improvement, a greater portion of the effort was concentrated in this area.

4.2.1 Concrete

One of the most widely accepted uses of fly ash is as a raw material ingredient in concrete. Structural and mass concrete, concrete block, pipe and precast products have consumed the largest quantity of fly ash in recent years. The use of fly ash as a raw material in the production of concrete serves two primary purposes: (1) to supplement or replace fine aggregate, and (2) to provide effective pozzolanic action. In addition to its physical properties which allow the concrete mix to flow easily, fly ash also possesses pozzolanic properties. Pozzolans are siliceous or siliceous and aluminous materials which possess in themselves little or no cementitious properties, but which in finely divided form will, in the presence of moisture, react chemically with calcium hydroxide at ordinary temperatures to form insoluble compounds possessing cementitious properties.

The currently available information indicates that, in general, when fly ash is used in portland cement concrete mixes, many of the concrete properties are improved. On the basis of findings published in the literature, and personal communications with representatives in the field of concrete technology, the effects of fly ash are summarized in Section 4.2.1.1. Although some differences of opinion in the industry exist as to the properties of concrete in which fly ash is used, the characteristics presented in Table 4-3 are considered a reasonable consensus of available information to date. These advantages and disadvantages are categorized by subject with references to source materials. Although these characteristics will vary in degrees depending upon the quality of fly ash and the proportioning of the concrete mixtures, the improvements afforded by fly ash can be realized when it conforms to the physical and chemical specifications issued by the Corps of Engineers, Bureau of Reclamation, TVA, etc., and when the concrete mixes are designed in accordance with those developed by Lovewell, Hyland, et al (C-58) or by R. W. Cannon (C-55).

4.2.1.1 Structural Concrete

The use of fly ash in ready-mix concrete is considered to be one of the more promising potentials for achieving mass utilization. In this application fly ash can be used to partially replace cement which is the highest cost bulk product with which fly ash can compete. According to the National Ready Mixed Concrete Association (C-92), the total production of ready-mix concrete in the United States during 1969 was approximately 186 million cubic yards. In addition, the market demand for ready-mix concrete is relatively stable.

The ingredients used to produce conventional portland cement concrete are portland cement, water, gravel or stone, sand, and a variety of chemicals to either increase the air content of the concrete or reduce the amount of water required for the proportioning of the concrete mixture. The amounts of each of these ingredients affect the concrete properties.

Table 4-3. Advantages and Disadvantages of Fly Ash in Concrete

Advantages

Characteristics	Source
Increased pozzolanic action	A-9, B-15, C-1, C-5, C-15, C-18, C-20, C-21, C-26, C-33, C-55, C-58, C-81, F-40
Improved workability	A-2, A-9, B-15, C-5, C-15, C-18, C-21, C-26, C-48, C-56, C-81
Higher long term strength	A-9, B-14, B-15, C-1, C-5, C-21, C-26, C-58, C-81, F-40, G-10
Decreased particle segregation	A-9, B-15, C-18, C-21
Decreased bleeding	A-9, B-15, C-18, C-21, C-26
Reduced drying shrinkage	A-9, B-15, C-15, C-21, C-26, C-81
Reduced alkali-aggregate reaction	A-9, B-15, C-21, C-26, C-58, C-81
Reduced cement-aggregate reaction	A-9, C-21, C-26, C-58
Improved resistance to sulfate action	A-9, B-15, C-20, C-21, C-26, C-33, C-58
Decreased permeability and leaching	A-9, B-15, C-1, C-15, C-20, C-21, C-33, C-48, C-56, C-58, C-81
Lower heat of hydration	A-9, B-15, C-20, C-26, C-58, C-80, G-10
Improved formability and surface wear resistance	A-9, B-14, B-15, C-33, C-56, C-58

Table 4-3. Advantages and Disadvantages of Fly Ash in Concrete (Continued)

Disadvantages

Characteristics	Source
Difficulty of transporting, handling, and storing fly ash as a separate material which runs like "liquid smoke"	A-9, B-15, C-15, C-26, H-13
Extra effort in batching and control of an additional ingredient in the concrete mix	A-9, B-15, C-26
Additional facilities, equipment, operations, overhead, etc., for extra ingredient	A-9, B-15, C-26
Additional air entrainment agents necessary to meet durability requirements	A-9, B-15, C-1, C-5, C-26, C-81, F-40
Maintaining uniformity in fly ash fineness	A-2, B-15, C-15, C-20, C-21, C-26, C-33, C-58, C-81
Maintaining uniformity in chemical composition of fly ash	A-2, C-15, C-26, C-33, C-58, C-81, F-40
No generally accepted specifications	A-2, B-15, C-33, F-40, H-13

The material flow through all ready-mix plants is basically similar. To accommodate the use of fly ash in a ready-mix concrete plant, additional equipment is required such as storage silos, conveyor systems, modifications to the batching control system, and, possibly, modifications to the liquid raw materials supply system.

In order to obtain a more realistic evaluation of the potential utilization of fly ash in ready-mix concrete, a review of the technology of producing and utilizing concrete was conducted (see Appendix C). In Appendix C, the technical factors considered in proportioning the ingredients used in producing concrete include the effect of using fly ash as an admixture. Economic proportions of fly ash are then established and used to compare the relative costs of producing concrete with and without fly ash. These data are presented parametrically to allow evaluation of the economics of fly ash concrete as a function of fly ash cost and transportation distance for different strengths of concrete.

4.2.1.1.1 Fly Ash Concrete

The following two sections deal with 28-day-strength, fly ash concrete proportioning and ready-mix economics. This portion of the study was performed to provide a better understanding of the correlation between two prominent fly ash proportioning procedures (TVA and that published by the ACI) and to determine if possible whether the economics related to ready-mix concrete production inhibits the use of fly ash. As a result of this survey, a close correlation was found between the two methods investigated, which removed any doubts about selecting proportions to use in an economics survey. The results of the economics survey are given in 4.2.1.1.2. Additionally, fly ash concrete advanced technology and technology improvements are discussed in Section 4.4.

The proportioning of ingredients for fly ash concrete in this survey were derived from experimentations conducted at the Tennessee Valley Authority (C-55) and at the Chicago Fly Ash Company (C-58). For these references, the work performed at TVA was conducted over the past eight years, while experimentations by the Chicago Fly Ash Company, whose results are reported by the American Concrete Institute, has spanned a 20-year period. An expansion of the technology for design strengths beyond 28 days is discussed in Section 4.4. Figure 4-6, derived from the TVA data, presents the amounts of cement and fly ash required in non-air-entrained concrete having equal 28-day strength as compared to pure portland cement concrete. Type I portland cement, 1-in. aggregate, 4-in. slump, and a ratio of 1.25 for required-to-specified compressive strength were used for the example illustrated in Fig. 4-6.

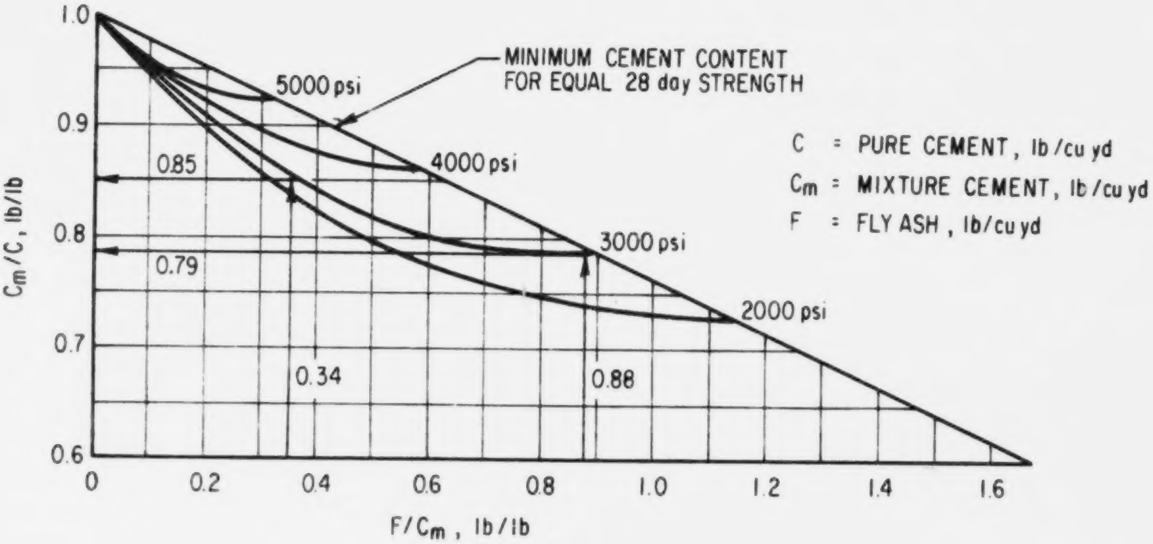

Fig. 4-6. TVA Fly Ash Concrete Proportions

The ordinate is expressed as the ratio of the cement in the mixture of fly ash portland cement concrete to the cement in non-fly ash concrete (C_m/C); the abscissa is expressed as the ratio of fly ash to mixture cement (F/C_m). The diagonal line, labeled "minimum cement content for equal 28-day strength," represents the minimum amount of cement required in a mixture, relative to pure portland cement to obtain equal 28-day strength.

The following is an example of proportioning for non-air-entrained 28-day fly ash concrete. To obtain 3000-psi concrete requires a minimum ratio of mixture cement to a pure cement of 0.79. By reference to Fig. 4-6, this would require a ratio of fly ash to mixture cement of 0.88. The amounts of cement and fly ash in the mixture would be computed as follows: For a portland cement concrete, the amount of cement is 470 lb as shown in Appendix C. The amount of mixture cement is obtained from

$$C_m = (C_m/C)C$$

and would be 0.79 (470) = 370 lb/yd^3 for the minimum mixture cement proportions. The corresponding amount of fly ash is obtained from

$$F = (F/C_m)C$$

and would be (0.88)(370) = 326 lb/yd^3. This, however, is not an economical proportioning.

Figure 4-7 (C-55) shows a TVA relationship for economic proportioning of fly ash for 28-day strength concrete. These proportions are claimed to obtain minimum total cost of the fly ash concrete for a given strength. As an example, if it is assumed that fly ash costs 36 percent as much as pure portland cement per pound delivered, and that it is intended to produce 3000-psi concrete, the figure indicates that a ratio of fly ash to cement in the mixture that would be most economical would be 0.34. By referring to Fig. 4-6 and entering at the 0.34 F/C_m ratio, it can be noted that this intersects the 3000-psi line at approximately 0.85 C_m/C.

Therefore, for 3000-psi, non-air-entrained concrete, using Type I cement, and the 0.36 fly ash/cement cost ratio, the amount of cement and fly ash in the fly ash concrete are:

$$C = 470 \text{ lb/yd}^3$$

$$C_m = 0.85\ (470) = 400 \text{ lb/yd}^3$$

$$F = 0.34\ (400) = 136 \text{ lb/yd}^3$$

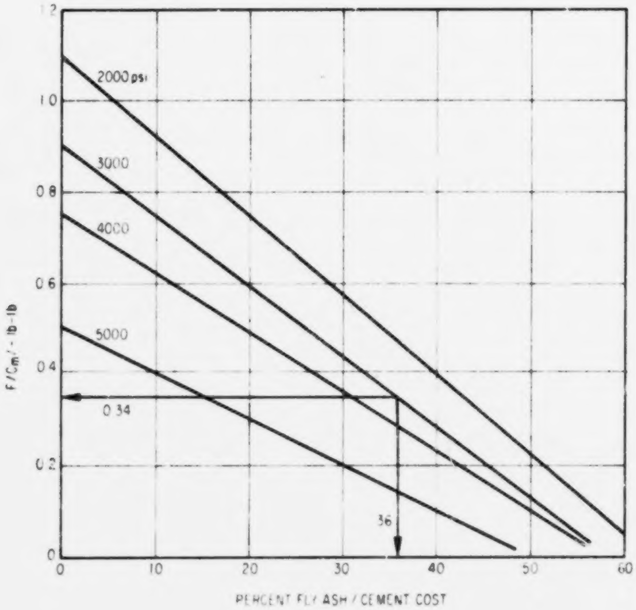

Fig. 4-7. Economic Proportions of Fly Ash for 28-Day Strength Concrete

Table 4-4 compares the amounts of cement in conventional concrete with the minimum proportions and with the economic proportions for the 0.36 fly-ash-to-cement cost ratio.

Table 4-4. Fly Ash Concrete - Minimum Cement Proportions and Economic Proportions

	Minimum C_m Proportions		Economic Proportions Fly Ash = 36% Cement Cost	
28-Day Strength Concrete, psi	C_m/C lb/lb	F/C_m lb/lb	C_m/C lb/lb	F/C_m lb/lb
2000	0.62	1.15	0.80	0.47
3000	0.79	0.88	0.85	0.34
4000	0.85	0.62	0.90	0.28
5000	0.93	0.32	0.94	0.33

The American Concrete Institute published Table 4-5 (C-58) providing the proportions of cement and fly ash in air-entrained and non-air-entrained concrete. Mix A uses only portland cement, Mix B uses portland cement plus water reducing agent, Mix C uses portland cement and fly ash, and Mix D uses portland cement, water reducing agent, and fly ash.

As explained previously, in comparing fly ash concrete with conventional concrete, it is necessary to obtain approximately equal strength at equal time periods in the curing cycle for the same design conditions. Tests conducted on proportions approximating the ACI fly ash concrete proportions (C-132) indicate that in general the one day early strength of the non-air-entrained concrete is somewhat higher than the conventional, the three-day strength is approximately equal to the conventional, and the seven-day strength is roughly 10 to 15 percent lower. At 28 days the strengths are equal, and at 90 days the fly ash concrete has a considerably higher strength than conventional concrete. The strength at which forms can be removed from the concrete vary from 500 psi to 1500 psi for normal type of construction work. These strengths occur in the one- to three-day period for most types of concrete. Since during this time period, the fly ash concrete either exceeds or equals the strength of the conventional concrete, it can be seen that for the ACI proportions the early strength of the fly ash and conventional non-air-entrained concrete can be considered equal. The somewhat lower strength of fly ash concrete at seven days is not considered important. For air-entrained concrete, the early strength of fly ash concrete is somewhat less than that of portland cement concrete, by as much as 20 to 25 percent in the one- to seven-day period, then equal at 28 days, and considerably higher thereafter. This is not seen as a deterrant to usage, particularly since curing conditions and form removal in actual practice are the same as for portland cement concrete.

Table 4-5. ACI Fly Ash Concrete Proportions

Line No.	Class of Concrete Compressive Str. at 28 days, psi	Max. Size Aggr. Inches	Max. Total Water per cu. yd. of Concrete gallons	Equivalent Minimum Cementing Material Contents per cu. yd. for 4 inch slump			
				Mix A	Mix B	Mix C	Mix D
Non-Air Entrained Concrete							
1	2500	1"	36	4½ Bags P.C.	4 P.C. + W.R.	3¾ P.C. + F.A.***	3¼ P.C. + W.R. + F.A.**
2	3000	1"	36	5 Bags P.C.	4¼ P.C. + W.R.	4¼ P.C. + F.A.***	3¾ P.C. + W.R. + F.A.**
3	3500	1"	36	5½ Bags P.C.	4¾ P.C. + W.R.	4¾ P.C. + F.A.***	4¼ P.C. + W.R. + F.A.**
4	3750	1"	36	5¾ Bags P.C.	5 P.C. + W.R.	5¼ P.C. + F.A.*	4½ P.C. + W.R. + F.A.**
5	4000	1"	36	6 Bags P.C.	5¼ P.C. + W.R.	5½ P.C. + F.A.*	4¾ P.C. + W.R. + F.A.**
6	5000	1"	36	7 Bags P.C.	6¼ P.C. + W.R.	6½ P.C. + F.A.*	5¾ P.C. + W.R. + F.A.**
Air Entrained Concrete							
11	2500	1"	34	4½ Bags P.C.	4 P.C. + W.R.	3¾ P.C. + F.A.***	3¼ P.C. + W.R. + F.A.**
12	3000	1"	34	5 Bags P.C.	4¼ P.C. + W.R.	4¼ P.C. + F.A.***	3¾ P.C. + W.R. + F.A.**
13	3500	1"	34	5¾ Bags P.C.	5 P.C. + W.R.	5¼ P.C. + F.A.*	4½ P.C. + W.R. + F.A.**
14	3750	1"	34	6¼ Bags P.C.	5½ P.C. + W.R.	5¾ P.C. + F.A.*	5 P.C. + W.R. + F.A.**

Table showing suggested trial mixes in combination with admixtures.
P.C. = Portland Cement
W.R. = Water Reducer as defined in ASTM C-494.
F.A. = Fly Ash as set forth in ASTM C-618, Class F.
Note: W.R. amounts should be used according to manufacturers directions (usually a specified amount per bag of Portland cement). Fly Ash should be 75 lbs where marked *; 100 lbs where marked **; and 125 lbs where marked *.**

Simply stated, the adjustments to the straight cement mix to secure equal 28-day strength are as follows. Approximately 3/4 to one bag less portland cement per cubic yard of concrete is used. This reduction is replaced with approximately 1-1/2 times as much fly ash by weight[*]. In order to correlate the TVA proportions with the proportions given by ACI, Table 4-5 has been converted into Table 4-6 and provides the amounts of cement, fly ash and water in terms of lb/yd^3, using non-air-entrained Mix C concrete as an example.

The last two columns show the results of an analysis that was performed to convert the values into the ratios used in the TVA economic proportioning system; namely, ratios of the amount of cement in the fly ash-cement mixture relative to pure cement, and the ratio of fly ash to the amount of cement in the fly ash-cement mixture.

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[*] The technology related to using fly ash as an admixture in portland cement concrete is discussed further in Section 4.4.

Table 4-6. American Concrete Institute Fly Ash Concrete Proportions for Mix C (Non-Air-Entrained, 1-in. Aggregate, 4-in. Slump)

Specified 28-Day Strength, psi	Fly Ash Concrete			Conventional Concrete	Analysis of Proportions	
	Mixture Cement "Cm" lb/yd^3	Fly Ash "F" lb/yd^3	Water "W" lb/yd^3	Cement "C" lb/yd^3	C_m/C	F/C_m
2500	353	125	300	422	0.83	0.35
3000	400	125	300	470	0.85	0.31
3500	446	125	300	516	0.86	0.28
3750	494	75	300	540	0.91	0.15
4000	517	75	300	564	0.92	0.14
5000	611	75	300	659	0.93	0.12

Figure 4-8 compares the TVA and the ACI data to determine how closely they relate to each other. The lines identified by the squares depict the minimum amount of portland cement in the mixture, represented by the diagonal line in the TVA proportioning curve, Fig. 4-7. The lines identified by the circles are plots of the TVA economic proportions for an assumed cost of the fly ash equal to \$8/ton delivered and a portland cement cost of \$22/ton. The lines identified by the solid dots are the proportions published by ACI shown in Table 4-6.

For the amounts of mixture-cement to pure-cement ratios, it can be seen that a close relationship exists between the economic proportions advocated by TVA and the proportions recommended by ACI. Minor variations in this example would be caused by varying the costs of cement and fly ash. Since the ACI proportions are generally accepted by industry, these were used for the following economic analysis.

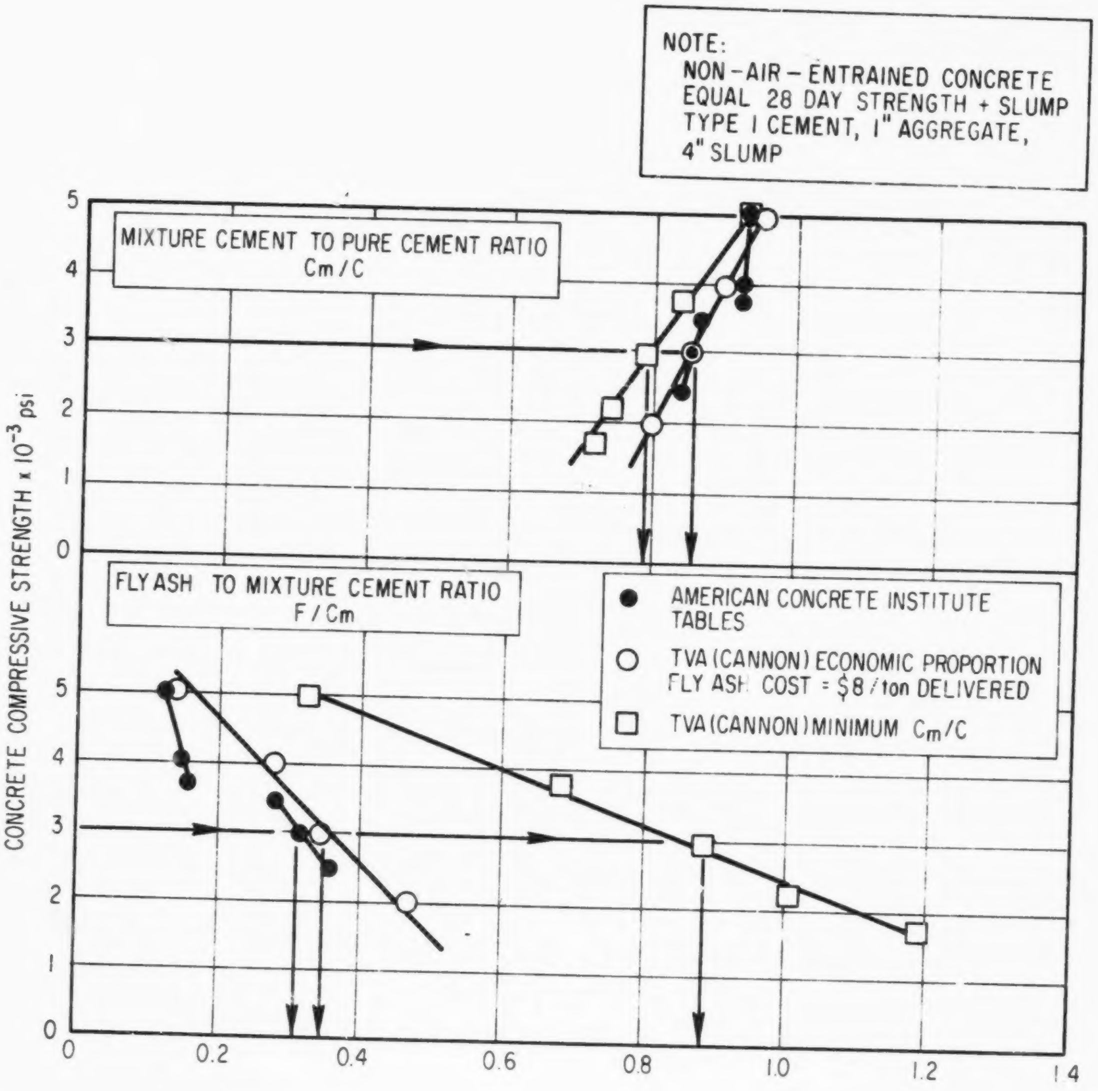

Fig. 4-8. TVA and ACI Fly Ash Concrete, Example Proportioning Comparisons

4.2.1.1.2 Fly Ash Concrete Economics

A cursory study of the economics of fly ash concrete related to the ready-mix operation was performed to determine if cost is an inhibitory factor. Details of this analysis are provided in Appendix C. A comprehensive cost analysis was not considered appropriate within the extent of this study because of the numerous, variable factors involved plus the variations in costs from region to region; the use or nonuse of beneficiation of the fly ash, brokerage fees, and financial assistance to ready-mix dealers for new equipment; and sliding costs related to local competition. The analysis was therefore limited to the more significant factors, using estimates made for costs of fly ash F.O.B. utility, cement, truck hauling, new equipment, and air entrainment. Several cases were considered, using variations in the parameters just mentioned. The results of that analysis indicate that non-air-entrained fly ash concrete costs approximately the same to produce as portland cement concrete at haul distances as low as 35 miles or as much as 150 miles, depending on the costs of the various input parameters. The effect of air-entrainment tends to increase the cost of fly ash concrete if the fly ash is high in carbon content, or high in particle surface area (Ref. B-18). An example case considered a four percent LOI fly ash, and according to the available literature, the cost of air entrainment agents could be as much as 20 cents per cubic yard. According to various users consulted, this may be somewhat conservative. However, applying this to the values determined for non-air-entrained concrete, the approximate fly ash concrete (4 percent carbon) comparison with portland cement concrete costs varies from a 7-cent cost increase if used at the fly ash source to a break-even cost at about 100 miles, depending on the inputs. It should be noted that most air-entrained concrete using one percent carbon fly ash for example, costs the same as non-air-entrained fly ash concrete. Also, the use of fly ash does not appreciably affect water reducing agent costs.

Strict conclusions cannot be drawn from this analysis because of the many cost variations involved for each case; however, indications are that (based on Table C-6 in Appendix C) a dealer can increase his profit before taxes by approximately 50 cents per cubic yard if high quality fly ash concrete is delivered within 10 miles of the fly ash source, or he can break-even at about 150 miles. However, if he acquires cement at $22/ton and fly ash at $4/ton F. O. B. utility, buys good quality or sophisticated storage and handling equipment which is replaced in five years, and uses a "poor" grade of fly ash, indications are that he will not be able to match portland cement concrete on an equal production economics basis.

In most cases, the dealer should be able to produce fly ash concrete to compete with portland cement concrete for haul distances of approximately 50 to 150 miles. Since the profit, before taxes, on portland cement concrete is in the range of $2 to $3 per cubic yard (according to various personal contacts), a potential increase of 20 to 50 cents per cubic yard would be appreciable to the dealer. If circumstances, as noted above, increase the cost to the dealer, it is generally small enough to be absorbed by the contractor who stands to benefit from the technical and economic advantages of using fly ash concrete.

As noted in Appendix C, in consideration of the utilization of "greater-than-28-day" design strengths described in Section 4. 4. 2. 1, the production costs of fly ash concrete for some applications can be reduced rather dramatically. Using this technology where applicable, cost reductions can be attained for any type of concrete, and for some it can be well in excess of one dollar per cubic yard.

In summary, fly ash concrete has technical advantages over conventional concrete, including improved workability, higher long-term strength, reduced drying time, reduced shrinkage, increased impermeability, increased resistance to sulfates, etc., as detailed in Section 4. 2. 1. These technical advantages result in a better finished product and some, such as improved workability, can result in lower placement costs for the user.

The technical disadvantages of fly ash concrete, including more complex handling and storing, more complex operations and equipment to produce the concrete, and fly ash quality problems, etc., generally affect the cost of producing the concrete. However, as long as the producer can sell fly ash concrete at approximately the same cost as conventional concrete (as indicated herein and in Appendix C), these factors have relatively little influence as economic inhibitions to the utilization of fly ash concrete. Limitations of haul distances are noted above.

4.2.1.2 Mass Concrete

Although the technical advantages that result from the use of fly ash in concrete are applicable to mass concrete, of primary interest is the reduction of heat generation. Portland cement concrete mixes containing fly ash that replace an equal amount of portland cement have a lower heat of hydration. Although the partial replacement of fly ash for an equal amount of portland cement in concrete mixes result in slow early strength development, this is not considered to be a disadvantage in mass concrete since it is generally not highly stressed. In most cases the stresses produced are the result of its own weight which is applied slowly as the structure is built.

The technical incentive for reducing the heat of hydration in mass concrete, which is well known throughout the industry, results from two basic problems. First, as the concrete near the surface cools, the differential in temperature between surface and interior may produce thermal gradients which result in tensile stresses exceeding the tensile strength of the early age concrete. Secondly, the interior concrete must eventually cool to the mean temperature of its environment and if it is cured at a high temperature and restrained against volume change, the cooling inevitably results in the development of tensile stress. Mass concrete structures which are not normally reinforced cannot hope to withstand the resulting temperature drops that approach 135°F without cracking. Although the total heat generated is similar to that of conventional portland cement concrete, fly ash concrete applied to the interior will defer a portion of the heat generation until the center of the mass has started to cool. Thus, the peak temperature is reduced as is the temperature drop to ambient.

Large construction jobs such as concrete dams, flood walls, retaining walls, and navigation locks offer an uncertain market for fly ash. Since the mass concrete market is irregular, the potential application of fly ash for such purposes can only be anticipated as opportunities appear. Each such project represents a separate potential with no continuing demand. As indicated in Section 4.3, fly ash utilized in mass concrete projects is purchased under specification with its use controlled to reduce the risk of improper application. In addition, since the specifications are somewhat strict as to the carbon content and fineness of fly ash, the supply may necessarily be limited to one or two sources with their locations a considerable shipping distance to the job site. Furthermore, considerable storage facilities are also required to fulfill the demand for large quantities of fly ash in a relatively short period of time. For example, the Dworshak Dam presently being constructed at Orofino, Idaho, is planned to utilize 200,000 tons of fly ash in the remaining 6.5 million yd^3 of concrete over the next four years. The fly ash is being shipped by rail from Chicago to Idaho in special covered hopper cars for a reported delivered cost of approximately $16.00/ton, most of which is transportation cost at one cent per ton/mile.

Fly ash concrete competes with artificially cooled portland cement concrete (e.g., ice placed in the mix) in mass concrete. With much of the mass concrete work today being performed in the western part of the United States, the use of fly ash is particularly sensitive to transportation costs. As these costs rise, the economic feasibility of fly ash usage rapidly declines. A partial solution to such a problem would be the utilization of lignite fly ash which is produced mostly in North Dakota and has been shown to be adequate, although not covered by present specifications, and the use of increasing supplies of fly ash from the Southwest.

A further improvement of fly ash usage for mass concrete would result from the incorporation of proportioning criteria such as that now used by TVA (see Section 4.3.2.6). For example, current fly ash concrete usage in Corps of Engineers and Bureau of Reclamation mass concrete projects employs an equal substitution of fly ash for cement on a 35 percent volume basis which is adequate for the purpose of reducing heat of hydration. Greater reductions of cement and additions of fly ash can be used technically, with the proportioning depending on the quality of the various constituents. This technology has been demonstrated by the U.S. Army Corps of Engineers, but is not used. However, it is used by the TVA where the fly ash supply is adequate and controlled by TVA, and transportation distances are comparatively short.

Although it is recognized that fly ash is a valuable admixture for mass concrete, and is used as such, the sporadic demand for this purpose and the limits on numbers of projects of this type do not allow for large increases in fly ash usage. The incorporation of new specifications plus the use of lignite, and an expanding economy all add up to increased fly ash usage; however, it is not expected to provide a large impact on the future growth or mass utilization potential of fly ash when considering the total volume produced.

4.2.1.3 Concrete Products

As might be expected, the allied concrete products industry which manufacture building block, pipe, and precast units, represents an attractive market potential for fly ash. Although most of the preceding general discussion regarding concrete applies to these products in varying degrees, there are certain features associated with the use of fly ash in their manufacture that distinguish them from general concrete construction. The curing used in the concrete product operations is usually conducted at elevated temperatures using saturated steam to produce heat and at the same time to maintain high humidity conditions, and in some cases high pressures. For these curing conditions, an equal replacement of fly ash for cement reduction can be tolerated without the disadvantage of low early strength. Also, since these processes are repetitive with the end product being duplicate units produced over and over again, the advantages of fly ash to these operations in reducing wear on forms and better molding qualities become considerably more significant.

Estimates for the concrete block industry (B-13) indicate a current annual production total of approximately 3 billion concrete building block units (8 x 8 x 16 in. equivalent). At an average rate of one pound of fly ash per block, which is in accordance with the accepted (25 percent) replacement of portland cement with fly ash by the American Concrete Institute, the theoretical fly ash utilization potential for this use becomes about 1.5 million tons per year. Although information is not available to determine the accessibility of fly ash to the block production plants, it is reasonably assumed that a more practical potential would not exceed one million tons per year. From information available in the literature and discussions with producers of concrete block, it appears that a savings on the order of 0.2 cents per block can be realized by the partial replacement of cement with quality fly ash costing $7.00 to $8.00/ton delivered.

No readily available information was located upon which to base an estimate for the fly ash utilization potential in the production of pipe and precast concrete. However, typical mix designs presented in the 1970 Concrete Industries Yearbook provide for a maximum replacement of 15 percent portland cement with fly ash.

From a technical viewpoint it appears that the concrete products industry represents a very attractive field for the utilization of fly ash. Based on the best currently available cost information, the transportation of quality fly ash to a concrete block plant beyond approximately 130 miles would become uneconomical. Therefore, it is estimated that if the concrete products industry were exploited to its fullest extent, this field would probably consume a maximum of 5 percent of the total annual fly ash production.

4.2.2 Lightweight Aggregate

The primary market for lightweight aggregate is in the manufacture of bulk and structural concrete as well as concrete block. Although its advantages in certain applications have been recognized only recently, the annual output in the United States is over 13 million tons (Ref. C-31), with the manufactured lightweights (e.g., made with clay, shale, slate or fly ash) experiencing the most rapid growth. The consumption of lightweight aggregates is expected to reach 55 million tons/yr within the next decade (B-15) while at the same time the supply of natural aggregate in many parts of the country is diminishing rapidly. Therefore, this growing industry offers what may be the best outlet known for the consumption of large quantities of fly ash. Additionally, with adequate developments, it may offer a market for the utilization of limestone-modified fly ash. To help meet this need for lightweight aggregate, several commercial processes for its manufacture from fly ash have been developed. However, these developments have not been extended to the stage that fly ash aggregate can compete economically with other lightweight aggregates.

In spite of the potential for the rapid growth of a lightweight fly ash aggregate market, the experience of six production plants built so far in the United States has not been good. Three have discontinued operations permanently: two for a variety of technical and economic reasons and the third because the utility providing the fly ash switched from burning coal to gas. A fourth plant is attempting to resume operations after being closed down for 3 years. The two remaining plants are in operation and are continuing in their development efforts to produce and competitively market a quality lightweight aggregate manufactured from fly ash. Although they use the same basic process, the type of equipment employed is different and has resulted in separate problems and development approaches. (There is one plant, Enercon, Ltd., near Toronto, Canada, now in its initial shakedown period; it is designed with substantial differences from the others and has not yet demonstrated its projected capabilities.) In order to appreciate production

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4.2.2.1 Technology - General Characteristics and Processing

Lightweight aggregates are generally defined as any solid material included within a concrete mix weighing 115 lb/ft^3 or less. Concrete made with conventional sand, gravel, or crushed stone has a unit weight of 140 to 150 lb/ft^3. However, structural concrete using lightweight aggregates can be produced with equal strength and a unit weight of as low as 80 lb/ft^3. Thus the use of lightweight aggregates permits architects and engineers greater flexibility in designing longer spans, larger floor areas, added height or simpler foundations, and this lightness of structural concrete has enabled it to be competitive with structural steel frames in high-rise buildings.

The various lightweight aggregates used in the United States are normally classified in three general categories: (1) natural, (2) by-product, and (3) manufactured. Natural lightweight aggregates are those derived from naturally occurring materials such as pumice and diatomite, and volcanic ash, cinders and scoria. Although these aggregates are very light, they produce concrete relatively low in strength. By-product aggregates are derived from the combustion of coal or coke and include slag and cinders which are used primarily for the production of concrete blocks. The manufactured aggregate category includes expanded clay, shale, and slate. Lightweight aggregate produced from fly ash is also included in this category. In general, the manufactured aggregates are highest in strength and can be used in both structural concrete and lightweight masonry blocks.

The two methods which presently account for about 95 percent of the manufactured lightweight aggregate (non-fly ash) produced in this country (Ref. C-97) are the rotary kiln and sintering processes. In both of these processes, clay, shale or slate are heated rapidly to the point of fusion;

while the material is in this state gases are evolved within it which produce bloating, and this results in a porous structure when the material is cooled which provides strength and a low bulk density. The sintering process is also used for manufacturing lightweight aggregate from fly ash. The use of fly ash has several advantages compared to clay and shale. This is because raw fly ash is a finely divided material which does not normally require pulverizing before sintering; it can be obtained without mining, and it contains carbon for the sintering reaction, which reduces fuel costs.

All processes for manufacturing fly ash lightweight aggregate are essentially identical. Fly ash is agglomerated, formed, sintered, and sometimes ground and screened. Agglomeration requires the addition of water (about 20 percent) and usually clay or organic binders depending upon the process. The wetted fly ash is usually pelletized so that the material will be held in the burner grates and so combustion gases can easily pass through the bed. Alternative forming by extrusion has been tried in one process but this technique has been replaced by a roll forming method using serrated rollers.

Pelletizing of the fly ash is one of the more important steps since variations in pellet size can affect the quality of the aggregate made in the subsequent sintering operation. Moreover, the conditions required to provide adequate sintering in one size fraction differ sufficiently from those for other size fractions. For example, at a given set of conditions a small pellet may oversinter, producing a hard, dense, nonreactive aggregate; the identical conditions may not provide an adequate degree of sintering in the center of a large pellet, producing a poorly formed, weak aggregate. Because the control of the sintering process is not absolute (chemical composition provides control limits, see following section 4.2.2.2), the operation requires close control of the pellet size. This control is provided by the pelletizing equipment.

After forming, the pellets are transferred to a continuously travelling grate that passes through a fire box where the residual carbon within the fly ash is ignited. This carbon provides an important source of power for sintering of the fly ash in two of the processes. In the Enercon, Ltd., process, residual carbon is burned away before pelletizing and all power for sintering is provided by gas or oil burners. After sintering at 1800 to 2100°F, the pellets are either transferred to a stockpile or screened, or crushed and screened before stockpiled. The sintered pellets can be stored in the open where they are not affected by the weather, and sophisticated hauling equipment is not required.

As for product quality, a recent report by the Portland Cement Association (Ref. C-33) concludes that measured physical properties of the several concrete samples made from commercially available fly ash aggregate fall within the ranges shown in the "Guide for Structural Lightweight Aggregate Concrete" of the American Concrete Institute.

4.2.2.2 Technology Limitations

The most important step in the process for manufacturing lightweight aggregate is the sintering operation. Nevertheless, when the carbon content of the fly ash is used as a primary source of heat, the draft control on the combustion air is the only operational control. This control requires limits on the carbon content of the fly ash which can be sintered into acceptable aggregate. These limits are a function of the design of the sintering furnace and can be influenced by the sinterability of the fly ash. The sinterability is dependent upon the fineness of the fly ash and the iron oxide content that acts as a flux. Since neither the carbon nor iron oxide contents nor the fineness of the fly ash are properties for which the process has control, the success of the operation has been totally dependent upon the quality of the pelletized material.

The quality of the ash that is acceptable for lightweight aggregate manufacture contains a narrow range of carbon content of nominally 5 (± 2) percent. The actual range that is acceptable depends upon both the iron oxide content and fineness. For most fly ashes, these sinterability factors do not vary significantly and since their effect on the process is not strong, they serve a secondary role in the sintering operation. However, their effect becomes important when the carbon content is close to its functional limit. For example, if the carbon content is low within its acceptable range and the iron content decreases or the fineness decreases, the ability to continue to make acceptable aggregate may be lost. On the other hand, at high carbon contents, an increase in iron content or an increase in fineness may oversinter or fuse the aggregate and it again may be unacceptable.

The process for making lightweight aggregate from fly ash being developed by Enercon, Ltd. (see Section 4. 1.) does not use carbon as a primary source of fuel. In this process the residual carbon within the fly ash is burned off in a preheater, and sintering is accomplished by auxillary burners external to the sinter bed. In this way, direct control of the sintering operation is attained but at the expense of an additional operation and a significant increase in fuel costs. A further measure of control is attained through beneficiation of the fly ash which provides to the sintering operation a controlled fraction of particle sizes. This process has the potential for providing greater reliability and reproducibility in product performance but, at the time of this writing, the process has not operated on a production schedule to provide the data necessary to evaluate its capabilities.

A lightweight fly ash aggregate operation observed in Germany is limited by an inability to consistently form the required size pellets and, occasionally, to obtain adequate strength. That operation blends fly ash having a 2 to 3 percent carbon content with pulverized coal to bring the total carbon content up to 5 to 6 percent for sintering. The fineness requirement for the ash is 30 to 35 percent retained on a 170-mesh sieve; for the coal, which is purchased in the pulverized form, the fineness should be the same as the fly ash. The inability to consistently produce ash of the proper fineness, at the adjacent power plant, has limited the aggregate operation. Pellets of various sizes are formed on each pelletizing dish; however, the portion of the total production suitable for use in concrete block is insufficient and sometimes structurally weak. (A grinding operation is not used in any phase of this operation other than to break up the cake after sintering.) Despite the problems, the operators are optimistic and the development of this operation is continuing.

4.2.2.3 Inhibitions For Use of Fly Ash in Lightweight Aggregate

Several technical factors have been identified in the production of lightweight aggregate from fly ash which have inhibited the development and growth of the fly ash industry. The most significant factor has been the restrictive limitations of the technology to accept the variability in quality of fly ash that is normally obtained from power plants. Laboratory and pilot plant operations do not reveal these problems because of their relatively limited capabilities. The Enercon, Ltd., process design is one solution to the major problem of carbon control; other solutions that are being used or planned include blending of fly ashes having different levels of carbon and blending fly ash with pulverized coal.

Another inhibiting factor has been the scale-up of pilot plant design to production machinery. The use, or abuse, of production equipment is far more severe than that encountered in a pilot plant. The production equipment for lightweight aggregate manufacture from fly ash has suffered from major deficiencies in mechanical design (see Appendix D). Excessive maintenance, repair and replacement of this equipment has further aggravated the growth of this industry. While not being the primary factor, these two manufacturing difficulties have been major contributors to the closing of at least one plant.

These factors have certainly inhibited the rate of growth of an industry which manufactures lightweight aggregate from fly ash; however, such factors are not unusual in an infant industry. Solutions to these problems are being actively sought and incorporated in the process operation, and it has been shown that a quality product can be manufactured.

To date, the two commercially producing fly ash lightweight aggregate plants in the United States have not been able to market their product competitively for a profit. Whether the manufacturing process and market can be sufficiently developed to economically compete with other lightweight aggregates remains to be seen.

Indications are that to successfully compete in the lightweight aggregate market, the aggregate plant would be most effective located adjacent to the power plant so as to minimize the handling of fly ash. Additionally, definite commitments by, or involvement of, the power company would be necessary to guarantee a dependable supply of the required quality of fly ash.

A significant increase in the utilization of fly ash in the manufacture of lightweight aggregate appears possible, but cannot be expected in the near future.

4.2.3 Portland Cement Manufacture

Another potential market for fly ash is utilization as a raw material in the manufacture of cement. Fly ash can be combined with cement in two ways: as an additive, or as a component in the raw cement batch.

As an additive in the cement manufacturing process, fly ash can be mixed with the finished cement or interground with cement clinker. Fly ash added at either of these two points in the manufacturing process remains as fly ash and although thoroughly blended into the portland cement, the resulting material will perform about the same functions subject to the same limitations as those obtained by adding fly ash to concrete mix.

Cement with fly ash additive must be marketed as a separate product (which is done in some instances), and as such, separate handling, storage, stocking, etc., are involved. Also, the blending of the two materials requires special techniques to ensure uniformity of the cement. The economics of handling and transportation do not allow for the mass utilization of fly ash in this manner without the combined cooperation of power plants and portland cement producers.

Used as a raw material in the manufacture of portland cement before firing, fly ash possesses chemical elements which are found in portland cement, but in different proportions. In the manufacture of the various types of portland cement, two or more raw materials must be blended to achieve proper chemical composition in the kiln feed. The most important sources for lime are cement rock, limestone, marl, shell, marble and chalk; for silica: sand, quartz, and quartzite; for alumina: clay, shale, and slag; for iron oxide: iron ore, pyrite cinders, blast furnace flue dust, and mill scale. The four major chemical components in the kiln feed are lime (CaO), silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). Although minor differences exist between the various types of portland cement, the raw material blend is generally 73 to 78 percent $CaCO_3$, 12 to 17 percent SiO_2, 2 to 5 percent Al_2O_3, 1 to 3 percent Fe_2O_3, 1 to 5 percent $MgCO_3$, and less than 1 percent alkalies (C-11). The potential raw material that fly ash can substitute for in portland cement is essentially the aluminous, ferrous and siliceous content of clay, shale, schist, and blast-furnace slag. In comparison to these, fly ash compares very favorably as a source of materials for blending with limestone in cement manufacture. An important chemical requirement of fly ash in the manufacture of cement is that it be uniform without appreciable variation in the composition as it is delivered to the cement plant. A uniform quality fly ash is necessary in order to avoid frequent costly and time consuming checks and adjustments of the raw mixture to maintain proper kiln feed composition.

The use of fly ash as a raw material eliminates the mining, crushing, and pulverizing process that is required for use of clay and shale. An additional advantage of fly ash results from the presence of carbon which can supply fuel for firing in the kiln. Also, it contains no water of crystallization, as do clay and shale, which must be driven off at the expense of heating.

In order to use fly ash economically, it would be necessary for the cement plant to be located near a coal-burning utility. Also, if a cement operation is stripping clay or shale to obtain underlying limestone, it will probably use that clay or shale in the raw batch whether or not fly ash is available nearby. As previously mentioned, the fineness and flow characteristics of fly ash require special handling, transportation, and dust collection equipment. Finally, and not of least importance if fly ash is to be used, is the fact that considerable capital investment in cement plant design and equipment must be committed to a fly ash raw material source which ordinarily does not make guarantees as to quantity and quality that will be available for future use.

Of the approximately 180 portland cement producing plants in the United States only three currently use fly ash as a raw material in their manufacturing process. Two of these three plants use fly ash merely for the purpose of making up for the alumina and iron deficiencies in the local clay. In each of these two operations, fly ash represents only about 4 percent of the raw mix. Neither of these operations is dependent upon the use of fly ash. If the availability or quality of fly ash were to become unacceptable, these plants could easily convert to comparable alternative materials, such as mill scale, and kaolin clay which are readily available.

The third plant, which is discussed in detail in the following paragraphs, represents the only cement manufacturing plant in the United States that exploits the use of fly ash to its fullest extent.

In Joppa, Illinois, the Missouri Portland Cement Company is located adjacent to the Electric Energy Incorporated power plant close to the Ohio River (C-116, C-117). This cement plant has a capacity of 5 million barrels annually and uses approximately one-half of the fly ash produced by the 1000 megawatt electric power plant.

The decision to locate this plant adjacent to the utility, approximately 70 miles from the quarry for limestone and sandstone, was based on several factors. Once the general area had been chosen because of accessability to major markets, the limestone quarry location was determined based upon the availability of limestone in the general area. The plant was, however, not located at the quarry site because of limited flat land above possible flood areas of the somewhat unpredictable Ohio River. After the determination that it was impractical to locate the plant at the limestone quarry site, a decision was made to locate adjacent to the utility and to use fly ash in place of shale, which normally makes up approximately 5 to 12 percent of the total raw mix. In this manner, it was possible to eliminate the quarrying of the shale, and reduce the operational cost considerably.

The operating process used at the Joppa plant is described in Appendix E. Wet and dry processing are shown; however, the Joppa plant uses the dry process only. An interesting aspect of the wet process is that it would technically lend itself to the utilization of limestone-modified fly ash; however, the related economics are generally unfavorable.

With respect to the economics of cement production, it can be noted that there are several special situations that exist in the case of the Joppa plant. The limestone which makes up the majority of the raw material is quarried at a site which is unsuitable for a cement manufacturing plant. Secondly, a river is available to transport the bulk of the raw material by barge from the quarry to the location of the manufacturing plant adjacent to the utility. It has been estimated that the cost of transporting by barge costs approximately 0.4 cents per ton/mile, not including the depreciation cost of the barges which are both designed and owned by the Missouri Portland Cement Company. In contrast, transportation by rail under the same conditions would cost approximately 2 cents per ton/mile, or roughly five times the barge cost. A major advantage of using fly ash is that a relatively small operating cost is required once the capital investment of the pneumatic conveying system from the utility is paid for as compared to the operational cost involved in quarrying shale.

It is estimated that the total cost of cement production is approximately one-third to one-fourth for raw materials and the remainder for operations and payment of capital investment. The capital cost of a cement plant is estimated at $10 to $15 per barrel annual capacity, so that a five million barrel annual capacity plant would cost from $50 to $75 million. The operational costs are divided evenly between fuel, electrical and labor costs. It is concluded that fly ash lends itself to the production of portland cement under certain special situations where the manufacturing plant cannot be located adjacent to the major raw material source or where possibly the limestone, sandstone deposits are located close to a utility. However, in most cases such special situations do not exist. This, coupled with the fact that there is no demand for new cement plants since the present market requires less than about 70 percent capacity, the potential for utilizing fly ash for the manufacture of portland cement is relatively low.

4.2.4 Bricks

The manufacture of brick from fly ash has been the object of several investigations, yet, no brick plant in the United States is currently using fly ash as a constituent even though its feasibility was demonstrated more than 20 years ago (Refs. C-99, C-53). The construction of such a plant in Western Canada has recently been reported, and will be the first of its kind.

4.2.4.1 Fly Ash Brick Technology

Because clay minerals are the most prevalent foreign material found in bituminous coals, fly ash is very similar in chemical composition to the clay and shale raw materials normally used in brick manufacture. However, fly ash exists as small glass spheres rather than as a clay mineral and physically behaves more like fine sand or silt and does not provide the plasticity associated with the clay minerals. As a consequence, while chemically similar, fly ash does not provide the properties required for forming processes (extruding) used conventionally for brick manufacture. An advantage can be gained by using fly ash as an ingredient in brick, especially with very plastic clays having a high clay mineral content, because the mixture could be formed by an easier extrusion operation. A series of clay-fly ash bricks were made at varying fly ash compositions up to 75 percent by weight in conventional brick making equipment. The results demonstrated that satisfactory products could be made with respect to strength, structure, absorption, and other physical properties (Ref. C-128).

An evaluation of bricks composed of fly ash and boiler slag fabricated in a conventional manner was made and the results indicated that the bricks were satisfactory with respect to strength, absorption, and durability (Ref. C-128). Bricks made of fly ash and sand were investigated in which the bricks were unfired and dependent upon pozzolanic reaction of the residual lime in the fly ash for strength development. This work demonstrated that selected cementitious fly ashes can be used with sand to make construction bricks or blocks.

The Coal Research Bureau of West Virginia University (WVU) has for some time been conducting rather extensive investigations of potential uses for fly ash. This research has resulted in the development of a process for producing brick from coal ash (Refs. B-15, C-17, C-53, C-98, and C-99). To establish the validity of their development theories through actual full-scale operation, a fly ash brick pilot plant was designed and built. From 1000 to 1200 bricks per day have been produced by this pilot plant which is limited by the capacity of the firing kilns. This process uses 74-percent fly ash, 23-percent bottom ash or slag and 3-percent sodium silicate binder. A description of this process is given in Appendix F. This process requires no raw material preparation other than sizing of the boiler slag, and, has resulted in a brick product that meets the requirements recommended by the ASTM. Another advantage of this process is the reported lighter-weight bricks that result and the proximity of fly ash raw material to the high density brick market.

As in most products that use fly ash, a uniform quality fly ash is important. In this process the final brick color, a function of the chemical content of the ash materials, can vary considerably. Excessive carbon content in the fly ash tends to retard oxidation of the iron and leaves voids that make the brick too absorptive.

As noted previously, fly ash bricks are not formed in the conventional extrusion manner. A dry press forming process is used which is usually a more expensive operation than an extruding process. However, the additional costs of this process would be offset by the elimination of the pulverization process normally used for clays and shale.

In summary, it is evident that discrete technological inhibitions to the use of fly ash in the manufacture of building brick do not exist. However, inhibitions do exist which interact with technology. Probably the greatest advantage of using fly ash is the opportunity to extend the life of a depleting supply of clay or shale used as a raw material in the manufacture of brick. Using fly ash as an additive to the clay or shale, satisfactory brick could be produced with the only cost being that necessary to handle and blend raw materials. However, in the last 10 years, four operators have exhausted their local source of raw material and have chosen to truck clay or shale from as far as 50 miles in order to continue operation.

4.2.4.2 Economics

In addition to the problem that present brick production exceeds the demand, the capital investment for constructing a new plant to manufacture bricks from fly ash would incur the risk of availability, quality, and cost of the necessary raw material. Moreover, the pollution problem presented by brick plants located near the source of fly ash in high density areas will be the object of increasing pressure and will result in costly equipment to meet the more stringent environmental requirements.

The work accomplished by the Coal Research Bureau of WVU has included not only the successful development of a fly ash brick process, but also included a detailed economic analysis. This method has been developed and programmed on an IBM 7040 computer to determine the potential economics of a proposed fly ash brick plant under widely varying conditions for any given marketing area.

Although over 1000 inquiries have been received by WVU since the announcement of the success of this development and numerous parties have seriously considered construction of a commercial brick plant utilizing this process, not a single plant has been constructed in the United States using this process, nor is there one currently known to be under consideration. Although all the factors that may have discouraged prospective entrepreneurs from constructing a fly ash brick plant are not known, it can only be reasonably assumed that their inhibitions, whether valid or not, were based on a combination of factors involving questionable quality and availability of fly ash.

Information was obtained on the investigation of fly ash brick in two major metropolitan areas located in different sections of the country. In the first case, a major electric generating utility obtained the interest of an investor for manufacturing fly ash bricks adjacent to one of their large coal burning plants. To assure the investor that fly ash from the specified power plant would be of adequate uniform quality, the utility in conjunction with WVU developed limits for fly ash physical properties and chemical composition necessary in the satisfactory production of bricks. Also, during the negotiation, the investor requested that the utility provide a stockpile of fly ash of sufficient quality and quantity to supply raw material for operation of the brick plant during the succeeding 10 to 15 years. Although the utility considered agreement to such a provision as a considerable gamble, the preliminary negotiation proceeded into an economic evaluation phase. Cost values encountered in the particular area were applied to the WVU economic analysis program. The results indicated that it would cost $40 per thousand for a plant to manufacture fly ash brick in this area. Upon relating these production costs for fly ash brick to the current market price of $38 to $55 per thousand for fired clay brick, the investor lost interest in the venture.

In the other case, the manufacture of brick was considered in an area where the availability of fly ash is particularly plentiful. This utilization of fly ash was considered by a major manufacturer that has accepted the use of fly ash in the manufacture of other products. He confirmed the comparative economic results reported in the first area and, in addition, concluded that fly ash would present more technical problems than clay and shale.

4.2.4.3 Potential Utilization

Geography plays an important role in the use of fly ash for brick manufacture. The principal sources of fly ash, in the North, Central and Eastern portions of the United States, are all close to ample sources of natural raw materials for brick manufacturing. Whether the coincidence of a depleting source of natural raw materials, a dependable local source of high quality fly ash, and a knowledgeable investor will soon exist may determine whether fly ash will eventually find an application as an ingredient in brick. This is not expected on a wide scale.

If there is no fear of early depletion of the locally available sources, the additional costs of handling and storage facilities will deter an operation from using fly ash in brick manufacture. Furthermore, since the industry is presently operating at over capacity, no new plants are planned for the immediate future. However, in the Western United States where clay and shale deposits suitable for brick manufacture are not as plentiful, the possibility for building new plants would be more likely except for the fact that fly ash is not readily available. (The new plant previously mentioned for fly ash brick manufacture is located in Western Canada where raw materials are not readily available, but fly ash is.)

From the foregoing discussion and the fact that present United States brick production capacity exceeds demands, it is not expected that this fly ash utilization potential will materialize to any appreciable extent.

4.2.5 Filler in Bituminous Products

4.2.5.1 Utilization Potential

The benefits of adding mineral filler to asphaltic paving mixtures has been fairly well established (Refs. A-9, B-15, C-49). Although mineral filler is not normally applied to asphaltic mixes for secondary type roads, its presence in mixes for primary surfaces is considered to provide increased stability and durability. For asphaltic surfaces that utilize mineral filler, only a small proportion (approximately four percent) of the mix is represented by this ingredient. Many different materials are accepted as filler types. These include limestone dust, rock flour, volcanic ash, hydrated lime, powdered shale, diatomaceous earth, portland cement, mineral sludges, bentonite clay, and fly ash.

Although from a technical standpoint, fly ash is not one of the better fillers in consideration of traction, its use does provide adequate pavement characteristics. Since filler requirements permit a maximum of 12 percent carbon content and a fineness of 70 to 100 percent passing a 200-mesh sieve, a low quality fly ash can be tolerated. Since low quality fly ash can normally be purchased at $1.00 to $2.00 per ton F.O.B. at the utility, fly ash becomes an attractive filler material for areas where other low cost filler types are not available. Further discussion of the subject is presented in Sections 4.3 and 4.4.

A major disadvantage of using fly ash as a filler in asphalt mixes is the difficulty associated with transporting, handling, and storing of the material. In addition, the use of fly ash would require special facilities to store fly ash as well as installation of dust collection systems to collect the fly ash that escapes in the plant during conveying and batching.

The flow of material through all asphalt plants is quite similar and is briefly described in the following paragraph.

Aggregates which include sand, gravel, crushed stone, slag, and mineral filler are fed from storage to the dryer where the moisture is removed and the aggregate heated. The heated, dried aggregate is continuously fed to vibrating screens which divide it into the specified separations. Each separation flows into its respective hot bin. The next steps are measuring and mixing where the proper amounts of aggregate from each hot bin and the correct percentage of asphalt are released and mixed to conform to the mix design.

Fly ash has been used successfully in bituminous products made in industrial plants such as roofing, filled mastics, plank, and similar commodities (Ref. A-9). Although this use can only account for relatively small quantities of fly ash, it is normally a year-round market, unlike the seasonal market of the construction field.

The use of fly ash as a mineral filler in asphaltic road surface mixes appears to offer an attractive utilization for fly ash from a technical and economic viewpoint. However, mineral filler is not used in all asphalt road applications and when used represents only a small portion of the mix. In addition to this market being a seasonal one, fly ash is not geographically and therefore not economically available to at least one-half of the United States. On this basis the full exploitation of fly ash in the bituminous products industry would not be expected to exceed one million tons per year.

4.2.6 Remote Filling of Mine Cavities

In the coal mining areas, mine subsidence damage to homes, bridges, and roads is an increasing problem. The increase is due only partially to additional mining. It can also be attributed to the growing need for urban and suburban land which has extended building over old mines, where slow deterioration of supporting conditions results in surface subsidence many years after mining has occurred. In addition to the subsidence, abandoned-mine fires have also become a serious problem in coal mining areas. The Bureau of Mines has developed a method for using fly ash to prevent and control the mine subsidence and fire problem (Refs. C-51 and C-133). This method remotely fills underground cavities by pneumatically injecting dry fly ash down boreholes drilled from the surface to intersect the mine voids.

Normally, fly ash is injected directly into the borehole from the trucks. The fly ash, which compacts during transportation, is refluidized by forcing compressed air through a perforated plate in the bottom of the sealed compartment. This operation, which takes two to five minutes, also pressurizes the compartment to between 12 and 15 psig. The valve at the bottom of the compartment is then opened and fly ash is drawn into a 25-ft long, 4-in. diameter feed line by the airflow. The air pressure in the compartment is not critical since the fluidized material would flow by gravity. When injected pneumatically through a borehole, fly ash exhibits good flow characteristics, flows readily, and has a very low angle of repose. Fly ash can be injected economically at a high rate of flow (0.5 ton per minute) without special nozzles or elaborate equipment in all kinds of weather. It fills voids and will harden without shrinking in the presence of moisture. The Bureau of Mines experimental work has indicated that from 200 to 1000 tons of fly ash per hole would be required to fill mine voids depending on their size.

The current experience of the Bureau of Mines in the Pittsburgh area indicates that the cost of this operation is \$2.00 to \$4.00 per ton of fly ash deployed in a mine cavity located within a 30-mile radius of the source of fly ash. This expense is also based on obtaining fly ash from the power plant at no charge. The cost for drilling a hole is about \$2.00/ft with the casing and adapter costing about \$20.00 to \$30.00.

Since many large coal burning power plants are located near the coal mining areas, the filling of abandoned mines appears to be an excellent means for utilizing/disposing of the entire amount of fly ash produced by these utilities (Ref. C-110). Since the utilities are currently incurring costs of up to \$2.00/ton to dump fly ash, the economics of this utilization may be justified, particularly when considering the potential increased value of the land above the mines.

4.2.7 Miscellaneous Uses

Other uses of fly ash in which large quantities can be potentially accommodated include agriculture and land reclamation, oil well cementing, grouting, mineral recovery, and ceramics. However, except for mineral recovery and ceramics, both of which require development programs, these uses were considered to have a low potential for the consumption of large quantities of fly ash in actual practice. Characteristics of some of the more significant of these are described in the following paragraph. Additionally, road base course applications offer a large utilization potential technically. This is discussed separately in Section 4.4.2.2.

4.2.7.1 Agriculture

From a technical standpoint, agriculture has the potential of utilizing the total annual production of fly ash. Some of the physical and chemical properties of fly ash that are considered advantageous for agricultural purposes include the ability to neutralize soils, the ability to retain more available moisture than many natural soils, and a loosening effect when mixed with tight and heavy textured soils. Fly ash can contribute to the neutralization of soil from either an acidic or basic condition, however, most fly ashes have a high pH, making them amenable to the neutralization of acidic soils. The proportionate amounts of fly ash to limestone required to achieve an equivalent soil condition or crop yield is sufficiently high as to be beyond consideration. For example, Ref. C-19 indicates that 600 tons per acre of fly ash is required for an equivalent growth of fescue attained by the application of limestone at the rate of 8 tons per acre. This investigation also reported that 200 tons of fly ash per acre could be used in the growing of corn, with larger applications creating toxic effects which lowered the yield. In addition, research results reported in Refs. C-19 and B-15 indicate that the plants which can tolerate all the chemical elements occurring in fly ash are quite limited.

Although this application appears to be a method for utilizing large amounts of fly ash, it does not seem to be economically attractive when compared to the use of lime or other additives to adjust soil pH. The transportation and handling costs for the large amounts of fly ash that would be required appears to be prohibitive. Moreover, the presence of certain trace elements often found in the fly ash would be detrimental to the growth behavior of many common types of vegetation.

4.2.7.2 Land Fill

The largest use of fly ash is as a land fill material -- whether the fill is required or not. When fill is not required, it is an expensive means of disposal of the fly ash; the cost normally varies from $0.50 to $2.00 per ton and is borne by the power company. However, if fill is required and hauling distances are short, fly ash can often be used more economically than other fill materials, and can provide technical advantages (Ref. C-73).

Among these advantages are ease of handling and spreading, low compaction density, and shear strength that continues to increase with time (a consequence of pozzolanic reaction with residual lime content in the ash). Fly ash, when covered with soil, provides excellent drainage for vegetation.

Optimum compaction occurs at approximately 20 percent moisture content and when fully compacted will exhibit shear strengths that double in 28 days and triple in 90 days. Early strength development is significantly lower for lower compaction densities but with time strength will approach the values of higher compaction densities.

The use of fly ash for land fill (excluding fly ash disposal) is not widely applied in the United States. It has demonstrated its usefulness in embankments and abutment backing in highway construction, but it is not widely used for these purposes because of the availability of natural fill materials.

An example of the use of fly ash in massive amounts as a roadway structural fill in England is given in Section 4.2.9. A special set of circumstances requiring a particularly high fill placed on deep alluvial soil favored fly ash structurally over locally available rock and soil. Except for special circumstances such as that, little use of fly ash as a land fill is expected except for disposal purposes.

4.2.8 Gas Concrete

Gas concrete is a lightweight cellular concrete widely used in Europe as a building construction material but not in the United States. It is also known as porous concrete, foamed concrete or cellular concrete. In its formulation and preparation, several European countries permit the liberal uses of fly ash as a pozzolan and as the siliceous filler (instead of, or together with, sand). For this reason, gas concrete manufacture appeared to offer a potentially large outlet for the consumption of fly ash in this country, and an investigation of its technology and applications was undertaken with the planning and assistance of the National Ash Association. As part of this effort, visits were made to facilities and sites in selected areas of Europe where gas concrete is produced and utilized. Organizations visited were the Robert Hildebrand Company, Stuttgart, Germany; H and H Industri, Copenhagen, Denmark; and Celcon, London, England.

There is an abundance of available literature pertaining to the history, properties, production, and utilization of gas concrete (see Appendix A, Refs. E-11, E-12, E-13, and E-16 through E-20). The following discussion deals principally with gas concrete as a utilization potential for fly ash. Published information is repeated only as necessary for clarity, and in most cases technical and economic data not available in the literature are included.

4.2.8.1 Material Requirements and Gas Concrete Properties

Each manufacturer of gas concrete has his own formula and procedure and there are no universally established materials requirements. However, the requirements are similar in that manufacture entails the use of powdered aluminum as the aerating constituent for a mixture of cement and/or lime, water, and a siliceous filler, and autoclave treatment of precast sections. Where fly ash is used, it appears that the fineness and silica content are the primary areas of concern, and that the requirements are lenient enough that most fly ash produced in the United States would be suitable. In this connection, it is interesting to note that at one European plant, fly ash from 12 different sources was used in a single day.

The following are ranges of fly ash properties requirements as used by several European producers, with notations on actual practice:

a. Fineness -

Blaine - 2500 to 3000 cm^2/gm minimum (2000 cm^2/gm has been used successfully)

Sieve - 10 percent retained on a 90-micron sieve; 35 percent retained on a 60-micron sieve

b. Loss on Ignition - 15 percent maximum, or 25 percent maximum of fly ash when combined with another aggregate, but total not to exceed 15 percent. (LOI is usually ignored unless a particular color is desired.)

c. Unreacted Lime - 2 to 4 percent maximum (up to 6 percent has been used successfully).

d. Sulphates - 2.5 to 3 percent maximum (up to 9 percent has been used successfully).

e. Silica - 50 percent minimum (as low as 40 percent has been used successfully).

f. Magnesia - 2 percent maximum (up to 3.5 percent has been used successfully).

When sand is used, the desired properties are:

a. Fineness - Same as for fly ash (see above).

b. Silica - 80 to 85 percent.

c. Magnesia and Mica - 2 percent maximum, each.

d. Feldspar - 10 percent maximum.

e. Clay - 6 percent maximum, by volume.

The lime and/or cement and aluminum powder should have a fineness equivalent to the siliceous filler. For lime, the slaking curve should be low with a temperature increase from 75 to 145°F occurring after about 15 minutes.

Fly ash concrete consists of 75 percent air and 25 percent solids; two-thirds of the air is trapped in closed spherical cells. The formulation most used in European building construction has a density of about 45 lb/ft^3 and a compressive strength of about 650 psi minimum. Strength modifications can be had through variations in material density, amount of cement used, autoclave conditions, and fly ash quality; however, the 45 lb/ft^3 material has proved to be adequate for both structural and nonstructural applications. The modulus of elasticity corresponding to this density is approximately 500,000 psi.

Fly ash gas concrete is a particularly good insulator. It has a thermal conductivity of 1.30 Btu in./ft^2-hr-°F when the density is 45 lb/ft^3, which is equivalent to that of wood and about one-sixth that of brick. When sand is used, instead of fly ash, the thermal resistance is reduced by a factor of about 2.5.

The acoustical insulating quality of gas concrete is not as good as that of ordinary brick or concrete, principally because of its low density. However, in areas where sound insulation is a problem, it has been shown that using a gas concrete 4-in. outer wall and a 3-in. inner wall separated by 3/4-in rock wool will provide a 56 db reduction compared to a single 4-in. wall.

4.2.8.2 Manufacturing Processes

The only practical process of importance today for producing gas concrete consists of autoclaving precast units. This is accomplished by thoroughly mixing cement and/or lime with a slurry of siliceous material and adding an aerating agent such as aluminum powder. This mixture is poured into molds, filling them about half way. (For panels which require structural stabilization, reinforcing steel rods previously dipped in bitumen are provided in the mold; vinyl coatings are not adequate. Also, large nonstructural panels are provided with small-gauge, unprotected steel rods to provide structural stability during handling.) There the aluminum reacts with the calcium hydroxide to produce hydrogen according to the formula

$$2Al + 3Ca(OH)_2 + 6H_2O \rightarrow 3CaO \bullet Al_2O_3 \bullet 6H_2O + 3H_2$$

The released hydrogen causes an expansion of the mass, approximately doubling its size. This occurs in 10 to 20 minutes, depending on the formulation used.

The material is then allowed to set for about 1-1/2 hours at 150 to 165°F. Setting must begin within 5 minutes of aeration completion to prevent the expanded slurry from falling. Setting before completion of aeration causes fissures which reduces strength. The mold walls are swung down, the rounded top of the set material is cut off, vacuum lifted and slurried to the original production slurry vat. The cutting operation is performed by automatic machinery resembling an egg slicer which divides the semirigid material into predetermined block or panel sizes. The piano wires of the cutting machine can be smooth or beaded to give the cut faces a particular surface texture.

After cutting, the mold sides are returned to an upright position and the mold/material unit is moved with numerous others into an autoclave where they are subjected to a pressure of about 10 atmospheres at a temperature of about 360°F in the presence of saturated steam. This condition is maintained for 6 to 7 hours for blocks, and for 11 to 12 hours for panels. The blocks or panels are then available for immediate use. Panels are occasionally provided with a decorative finish, in the factory, such as an aggregate surface or an acrylic containing fine marble chips.

Although the gas concrete can be used immediately after autoclaving, a drying out process occurs naturally which is not detrimental to the material. In this process, a 50 lb/ft^3 finished block, which contains approximately 20 percent water, drops in density to 47 lb/ft^3 in 2 months, and stabilizes at 44 lb/ft^3 in 12 to 18 months.

A current production formulation for gas concrete utilizing large amounts of fly ash consists of 80 percent fly ash, 20 percent portland cement, 0.05 percent aluminum, and water sufficient to form approximately 38 percent the weight of the dry materials. Numerous variations exist depending on the availability and quality of materials, and the research that has been performed by a producer. Some processes employed today use sand and no fly ash, with a lime/cement mix, and some use 8 percent fly ash and 78 percent sand, with the remainder a mix of lime and cement. All use a siliceous slurry and add 0.05 to 0.06 percent aluminum powder. According to the literature, small quantities of setting accelerators or hydration retarders also may be used.

It should be noted that when sand is used, a grinding operation is required to obtain the necessary fineness of the sand; this operation is not necessary when the total siliceous material is fly ash. Other factors that favor the use of fly ash instead of sand are that the fly ash improves strength and can improve shrinkage resistance. Moreover, it can be transported to the production facility containing as much as 40 percent water which negates the need for sealed shipping containers and sophisticated handling equipment.

4.2.8.3 Applications

Gas concrete is normally cast into blocks or panels and used as structural or nonstructural walls, partitions, floors, ceilings, or roofing. It can also be prefabricated into complete wall or room sections. Applications are for single family dwellings, multistory apartment or commercial buildings, and factories.

In addition to its excellent thermal insulation properties and reasonably high compressive strength combined with light weight, gas concrete offers other advantages such as fire and frost resistance, freedom from termites and decay, and negligible shrinkage and expansion factors. Its lightness (about 1/3 to 1/4 that of ordinary concrete), of course, simplifies construction costs and, for multistory buildings, can also mean great savings in foundations and structural framework. It is easily workable: it can be sawed, plained, drilled, nailed, and routed with ordinary hand tools.

Structural gas concrete buildings (without framework) are limited to three stories. Only a poured concrete shear ring is used at the periphery of the building between floors. In this form of construction, steel rods are inserted in the grooves between the steel-reinforced panels which can be 2 to 4 feet wide and approximately 10 feet tall and 4 to 10 inches thick depending upon the structural usage (ceiling slabs can be 20 feet long if necessary). The rods placed between the panels are connected to adjacent panels such that the entire structure is an integral unit, i.e., it is a monocoque form of a construction making it resistant to tornado and earthquake loadings. The slabs are glued together to prevent air passage, and grouting is only used to retain the stabilizing rods and, if desired, to provide a smooth finish at the joints. In most cases, the chamfered edges are not filled in with grouting thereby giving a distinct panel appearance. The surfaces are smooth enough to allow the inner surfaces to be lightly sanded to form a final finish, or they can be painted or papered. Usually the surfaces of outer walls are painted with a silicone, primarily to prevent sweating of the inner wall. Vapors which exist inside a house can escape through the wall; however, moisture droplets formed by rain or condensation are large enough to not penetrate the wall and, therefore, the inner walls stay dry. In addition, moisture held by the panel tends to alleviate problems of low humidity during dry periods by releasing moist air into the building.

Some typical construction applications are shown in Fig. 4-9.

4.2.8.4 Economics

The most attractive quality of fly ash gas concrete is the economic advantage it offers over other forms of building construction. In West Germany it has been noted that the cost of building construction, less land, can be reduced by 20 to 30 percent for conventional brick, block, or concrete homes, and large buildings or developments, respectively. More explicitly, erected gas concrete panels cost approximately half that of poured-in-place concrete, with an appreciable portion of that saving due to a 25- to 30-percent labor cost reduction. Further studies of the economics of building construction in the United States are necessary to accurately assess cost savings. However, indications are that the savings would be appreciable since a significant factor in gas concrete economics is labor reduction.

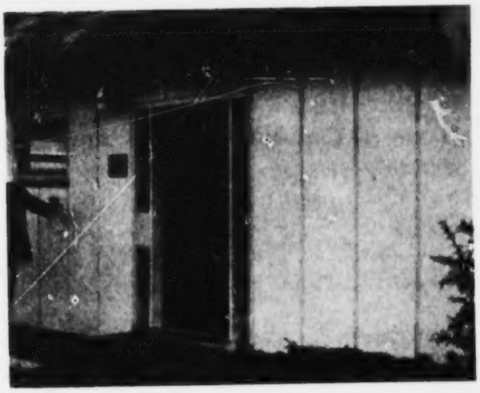


Fig. 4-9a. Structural Panels

Fig. 4-9b. Multistory Building, Nonstructural Panels

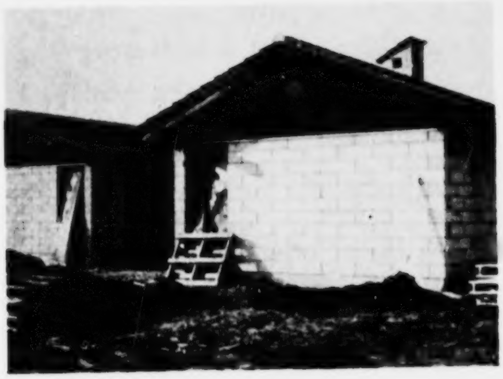
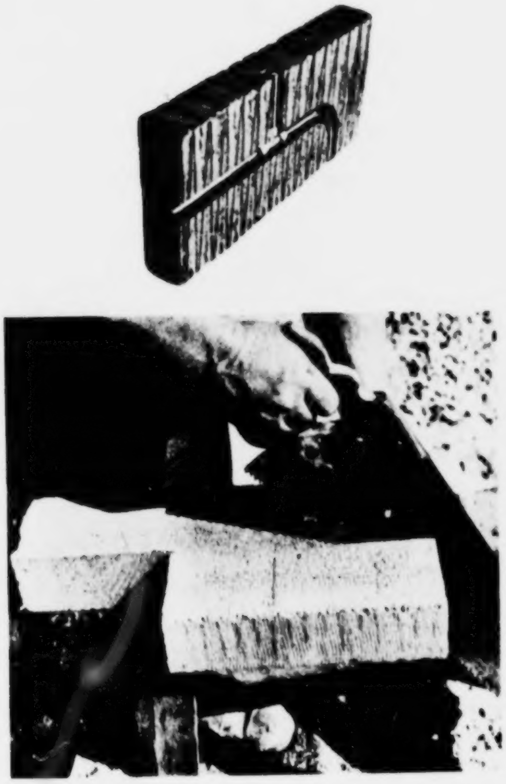


Fig. 4-9c. Load-bearing Blocks



Ref. E-11

Fig. 4-9d. Gas Concrete, Hand Work Features

Fig. 4-9. Typical Construction Applications

Some miscellaneous installed-panel selling prices of German panel construction, six inches thick, are as follows:

Non-load-bearing	-	\$ 0.56/ft^2
Load-bearing	-	\$ 0.65/ft^2

German masons are paid approximately \$2.25 per hour, and cement sells for about \$16 per ton.

Varying estimates of constructing a minimum-size gas concrete plant in the United States, producing 65,000 to 100,000 yd^3/yr, are put at \$2 to \$3 million, excluding land. The use of fly ash instead of sand would delete the cost of grinding equipment, which represents 10 to 12 percent of capital costs (about \$90,000), and eliminate 15 to 18 percent of the production cost. It is also estimated that a small plant producing about one-third as much as the above on a two-shift basis, with direct casting instead of cutting and by using fly ash instead of sand, would cost about \$800,000.

4.2.8.5 Usage Potential for Fly Ash and Limestone-Modified Fly Ash in Gas Concrete

European utilization of gas concrete has proven it to be a highly desirable form of building material from the standpoint of construction economy and structural qualities. It is used in at least 20 countries; in West Germany, for example, gas concrete is used in the construction of 80 percent of all new factory buildings while in Sweden such use approaches 100 percent. Additionally, in the Philippine Islands it is now being used for the construction of low-cost housing projects.

Much of the gas concrete produced incorporates large amounts of fly ash. For example, in England in 1971 it is expected that 1 million tons of fly ash will be consumed. Since fly ash improves the quality of gas concrete, reduces capital and production costs, and is available in abundance in urban areas, it could conceivably find a large market throughout the United States as a constituent of gas concrete.

The future of gas concrete in this country is not readily assessable. As a new industry, it would have to compete with numerous well-established building techniques using conventional materials. To establish fly ash concrete as a building construction material on a wide scale would require substantial technical and economic surveys, coupled with the dissemination of the technology. Its acceptance, of course, could be accelerated through the construction and operation of at least one plant in the United States. For a bare-minimum plant or a plant the size of the largest available engineered plant by European standards, estimates of fly ash utilization are 7,000 and 45,000 annual tons, respectively.

Wet-collected limestone-modified fly ash also has an apparent potential for utilization as an ingredient of gas concrete. Theoretically, the amount of free lime in the ash would be less than 5 percent (see Table 5-1), and there would not be any unreacted sulfur. However, the silica content may be inadequate (15 to 30 percent versus 40 to 50 percent required) and a sand additive may be required. Because of the necessity for sand grinding, gas concrete incorporating modified fly ash would be more expensive than if regular ash were used. Its manufacture would be further complicated by the fact that the content of silica and other constituents would vary considerably, depending on the sulfur content of the coal and the efficiency of the boiler. Nevertheless, these apparent disadvantages do not rule out the possible utilization of wet-collected, limestone-modified fly ash. A program of chemical and physical characterization and utilization research is necessary to evaluate its true potential.

4.2.9 Foreign Utilization

Information on the utilization of fly ash by Japan, and by West Germany, England, and Denmark was gathered during the study. Data were also reviewed for the production and utilization of combined bituminous ashes in 1967 by the three above-named European countries and seven others (as shown in Table 4-7)*. In Europe, the indications are that the utilization of fly ash continues to increase and exceeds that of the United States in total fly ash used and in percentage used of the total produced.

The current annual bituminous coal fly ash production in West Germany is estimated to be 1.1 million tons, with an additional 5 million tons of bottom ash. This ash is produced in wet-bottom cyclone furnaces, and has a high carbon content after the first burn. Since this type of boiler allows reinjection of the fly ash (which is 40 percent of the original total ash) until the carbon content is reduced to 6 percent or less, the fly ash is approximately 16 percent of the total ash produced. Large quantities of lignite are also burned in Germany in dry-bottom furnaces, producing about 6 million tons of fly ash annually. However, none of this ash is utilized.

The German government controls the use of fly ash as a cement replacement in concrete. Presently, only one unit of one powerplant is certified to sell fly ash for this purpose, and one other is expecting certification soon. A one-year period of government inspection of the powerplant on a random, unannounced schedule is required prior to certification.

In England, the predicted 1971 production of fly ash is approximately 9 million tons. Six million tons (70 percent) of this will be utilized: over 2-1/2 million for load-bearing fill in highway construction, and one million as an ingredient in gas concrete blocks for internal wall linings and partition walls. The major portion of the remainder is used as a cement replacement in concrete.

In Japan, approximately 5 million tons of fly ash were produced in 1969 and 26 percent of this was utilized. More than 70 percent of this usage was for the manufacturing of cement or for the replacement of cement in concrete.

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* Further information is available in a report prepared by the Economic Commission for Europe, Committee on Electric Power (Ref. E-21).

In some cases in these countries, the utilization of fly ash is enhanced through government issuance of standards, e.g., for the use of fly ash in concrete. The eventual utilization of fly ash, however, generally evolves from research, resultant technology, and most importantly, economics.

As mentioned, Table 4-7 shows the European bituminous ash production and utilization for 1967. Except for the data on German ashes, these data apply to combined values for fly ash, bottom ash, and boiler slag. As noted in the table, 48 percent of the total European ash is utilized for roads, dams, and fill, while 46 percent is used for construction materials and cement binder. (Utilization of ash in the United States is in comparable proportions, however, in lesser total tonnages.) Of the 12,501,000 tons of total ash utilized in the ten countries identified on the chart, 82 percent was used in England, France, and Germany. In England, it is known that fly ash is used in large quantities as noted above; in France it is used principally as a cement additive and as a road fill or base material. Over 60 percent of all coal ash produced in France is utilized. Government ownership of mines, power companies and roads, plus an underproduced cement industry and a lack of borrow pits, aids this situation, but exact fly ash data are not published. Total coal ash produced in France in 1970 is estimated at 4.5 million tons; and in Germany it is exported in nominal amounts to neighboring countries for fill material in asphalt road building as well as being used locally for secondary roads and concrete block manufacture.

Preliminary estimates identify English and French usage of fly ash as that which causes the total European fly ash usage to rate well above America's. This is due principally to the control of the coal burning utilities by the government, coupled with the desire of the government to use fly ash, and the existence of an economical market for fly ash utilization.

Table 4-7. Foreign Production and Utilization of Bituminous Ashes - 1967 (Fly Ash, Bottom Ash and Boiler Slag)

Country	Production 1 000 Tons (Metric)	Utilization 1 000 Tons	Utilization Percent	Cement Binder 1 000 Tons	Con-struction Materials 1 000 Tons	Roads Dams Fill 1 000 Tons	Misc. 1 000 Tons
Belgium	1,300	557	42	54	254	224	25
West Germany							
Fly Ash	900	680		70	300	200	110
Bottom Ash	4,500	3,000		-	1,700	1,100	200
Slag	800	600		-	-	400	200
	6,200	4,280	69				
Denmark	340	321	96	34	34	181	72
England	9,500	3,993	42	57	1,295	2,504	137
France	3,700	2,026	55	887	111	999	29
Poland	3,300	1,025	31	-	785	230	10
Romania	240	24	10	-	-	-	24
Spain	860	1,000	12	23	1	76	-
Czechoslovakia	1,100	175	16	10	125	40	-
Turkey	170	-		-	-	-	-
Total (1 000 Tons)	26,710	12,501	47	1,135	4,605	5,954	807
% of Ash Utilization		100		9	37	48	6

As for technological advancements, the European use of fly ash in gas concrete (see Section 4.2.8) is the outstanding application noted that was superior to, or nonexistent in, American utilization. However, efforts to introduce gas concrete in American building construction are being made, and the American Concrete Institute has established a committee to study and recommend specifications for gas concrete.

Other applications of a less sophisticated nature, but still using fly ash somewhat differently or more abundantly than in the United States, include:

a. Asphalt Filler in Paving - A West Germany utilization called "Gans Paving" for secondary roads, 28 percent fly ash versus 4 percent in the United States (see Section 4.5.4).

b. Highway Structural Fill - An English procedure using 100 percent fly ash for high embankments placed on alluvial soils, in the construction of primary roads (see Section 4.5.4).

c. Base Course Materials for Parking Lots - An English usage, 88 to 90 percent fly ash, plus cement and water (see Section 4.5.4).

d. Abandoned Sewer Fill - An English application using mix approximately the same as in item c. The slurry is pumped into abandoned sewers.

Individual discussions of these fly ash utilizations are included in separate sections as noted by the reference paragraphs.

4.3 FLY ASH SPECIFICATIONS AND PROPERTIES

4.3.1 Introduction

The objective of this portion of the study was to examine the existing specification literature pertaining to fly ash, and to form an assessment of the extent to which present specifications enhance or inhibit the utilization of fly ash.

The most significant group of specifications pertains to fly ash for use as a pozzolanic admixture in portland cement concrete. Summaries of fly ash analyses and physical property data were compared with the requirements of several of these specifications. It was possible to identify the portion of fly ash which did not meet the requirements. ASTM C-618-68T was the most lenient of the specifications, but only 61 percent of the sampling met its provisions. The most severe were TVA Construction Specification G-30, Class I ash, and certain Bureau of Reclamation specifications; only 30 percent of the samples conformed to these. There were numerous instances, however, of the successful use of nonspecification ash in concrete mixes.

The following conclusions can be made:

a. Specifications as currently written contribute to the inhibition of the widespread use of fly ash in portland cement concrete.

b. Nonspecification ash can be employed successfully, but technological development is required.

c. Certain provisions of the fly ash specifications bear little relevance to the performance of fly ash in a concrete mix. Specification modifications are indicated.

d. Specifications on fly ash for use in products other than portland cement concrete are few in number but are in no way inhibitory.

e. Specifications for fly ash do not exist for numerous products in which it is used. However, in these cases specifications do exist for the products themselves. These specifications inhibit the use of fly ash only when the existing technology limits the selection of materials for reasons of incompatibility with the production technique, e.g., certain grades of fly ash in sintered aggregate production.

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4.3.2 Specifications Applicability

Specifications pertaining to fly ash generally are of two types: (1) raw material specifications, and (2) product specifications. Raw material specifications provide for the use of fly ash as a batch ingredient for a specific product or class of products. They specify the chemical and physical requirements for the ash in various levels of detail, depending on the level of technology required in the manufacture of the product. Typical of the raw material specifications are:

a. ASTM C-618, Fly Ash and Raw or Calcined Natural Pozzolans for Use in Portland Cement Concrete

b. ASTM C-593, Fly Ash and Other Pozzolans for Use with Lime

c. ASTM D-242, Mineral Filler for Bituminous Paving Mixtures

Product specifications deal only with the requirements or properties of the product, and mention peripherally or not at all the properties of the ingredients. They typically state that fly ash may be a constituent of, say, a blended hydraulic cement, a lightweight aggregate, or certain masonry units. The product specification is of limited pertinence to the present study because it does not constitute a direct inhibition to fly ash use.

Fly ash specifications have been published by advisory bodies such as the ASTM and the American Petroleum Institute, a regulatory body such as the General Services Administration, and by various users of fly ash. These specifications differ in certain significant, and not-so-significant, particulars as will be detailed later. Probably the most prestigious of the specifying bodies is ASTM. For example, ASTM C-618 and its evolutionary precursors have set the tone for several specifications on fly ash for use in portland cement concrete. Its acceptance is such that many users of fly ash simply stipulate that the ash conform to the appropriate ASTM specification per se, or with specific modifications.

4.3.3 Fly Ash for Use in Portland Cement Concrete

4.3.3.1 Development of Specifications

Probably the most technically demanding application for fly ash, and certainly the one that has received the most attention in the technical and specification literature, is as an admixture in portland cement concrete. Initial investigations of this application date from the early 1930's, and the report which served as the foundation for the specifications, methods of testing, and use of fly ash in cement was published in 1937 (Ref. C-122).

During the late 1940's, representatives of firms marketing fly ash began to urge ASTM to prepare standards under which fly ash could be marketed in the cement and concrete industry. The matter was assigned for committee action. After numerous iterations, ASTM C-350 was evolved, approved, and issued in 1954. It was then modified in 1957, 1960, 1963, 1964, and 1965 to accommodate new information. Finally, in 1968 it was combined with ASTM C-402 (Natural Pozzolans) to form the current ASTM C-618. Additionally, the Bureau of Reclamation, U. S. Army Corps of Engineers, and other agencies developed and published their own specifications.

4.3.3.2 Provisions of Specifications

As stated, the specifications published by various agencies differ in a few important provisions. These differences can be seen in Table 4-8 which details the chemical and physical requirements for fly ash provided by a number of specifications.

With reference to ASTM C-618, a major difference between it and all of the others shown is the allowable loss on ignition (LOI). ASTM permits up to 12 weight percent, while all other specifications require maxima of 5 to 6 percent. The LOI, in weight percent, corresponds very closely to the residual unburned carbon remaining in the ash. Excessive carbon is undesirable on at least two counts. One is that the carbon, which is generally coarse, decreases the pozzolanic activity of the ash and also the desirable workability which the ash imparts to concrete. Possibly more importantly, carbon interferes with the normal action of air-entrainment in concrete, which is required to impart weathering resistance to concrete. For example, an ash with an excessive carbon content may necessitate that the concrete batch contain upwards of 20 times the normal dosage of air-entraining agent for a satisfactory level of air-entrainment. Furthermore, high carbon content makes air-entrainment difficult to control. A further objection to carbon is that it may impart an undesirable color to concrete and thereby create adverse consumer reaction.

Two federal agencies, the Bureau of Reclamation and TVA (for Class I ash), impose maxima of 10 to 12 weight percent on the amount of residue retained on a 325-mesh sieve. Neither ASTM, the U. S. Army Corps of Engineers, nor the Federal specifications provide for a 325-mesh-sieve residue limitation. TVA mitigates their specification by providing additional specifications: Class II ash and Class III ash may contain up to 22 percent and 32 percent 325-mesh residue, respectively.

The justification for a sieve fineness specification is similar in some respects to that for a carbon limitation. The pozzolanic activity of fly ash is usually directly related to its fineness, and the residue on a 325-mesh sieve is usually regarded as just inert particulate material. Moreover, it may be highly carbonaceous, with its concomitant inconveniences. The exception provided by TVA in specifying ashes of different finenesses reflects their concept that a coarse ash may be a useful raw material, but it will require different concrete mix designs.

There are other differences in certain allowable chemical and physical properties called out by the specifications in Table 4-8 . These differences are generally minor, and are not felt to be highly significant to the performance of fly ash in a concrete mix. Only experts having a particular bias are apt to contend strongly that the difference between, for example, 3.0 and 3.5 percent SO_3, or 1.5 and 2.0 percent alkalies will affect substantially the utility of a fly ash. No scientific data supporting such contentions were found.

As the foregoing shows, there presently is no standard or specification which is universally accepted. In effect, each user agency has written its own specification. A movement is afoot to establish Federal

Specification SS-P-00570b (Ref. F-41) as a uniform standard which would be acceptable to all government agencies. This document is nearly identical to Corps of Engineers Specification CRD-C-262-63 (Ref. F-50), but requires only half as much qualification testing of fly ash. However, SS-P-00570b's lack of provision of a maximum 325-mesh-sieve residue is likely to cause objections by some agencies. And so the difficulties of standardization remain unresolved.

4.3.3.3 Specifications Versus Fly Ash Properties

It is instructive at this point to examine the specification requirements in light of how they compare with chemical analyses and physical properties actually measured on typical samples of fly ash. Two fairly large and reasonably complete bodies of data (Refs. C-9 and C-34) on fly ash were consulted. The reported properties of 59 fly ashes are tabulated and compared with the pertinent properties called out by several specifications. Chemical specifications and sample analyses are shown in Tables 4-9 and 4-10. The key physical specifications and the fly ash properties, as available, are presented in Tables 4-11 and 4-12.

The most frequent chemical delinquency of the ashes in these samplings is their LOI. Only a few other instances of chemical nonconformity are noted and some of these are for ashes that are clearly atypical. Also apparent is that virtually all of the ashes shown in Tables 4-9 and 4-10 meet the ASTM LOI requirement, but many of them do not conform to the LOI requirement of the other specifications.

Physical property data on fly ashes generally are quite limited. For example, available survey data seldom report compressive strength of mortar cubes, pozzolanic activity index, and many of the other physical requirements detailed in Table 4- 8 . The most frequently reported properties are the Blaine fineness (or specific surface area) and the 325-mesh-sieve residue. The data presented in Tables 4-11 and 4-12 are limited to these latter properties. Clearly, a large portion of these samplings is deficient by one or both criteria.

Tables 4-9 through 4-12 show that the key criteria provided by these

Table 4-8. Specifications for Fly Ash as an Admixture in Concrete

Property	ASTM C-618-68T	CE CRD-C-262-63	Federal SS-P-570b	Bu Rec 3172; Bu Rec DC-3413	TVA G-30 (Class I)	TVA G-30 (Class II)
$SiO_2 + Al_2O_3 + Fe_2O_3$, min, wt %	70	70	75	SiO 40, Al_2O_3 15	75	75
MgO, max, wt %	--	5.0	5.0	3.0	5.0	5.0
SO_3, max, wt %	5.0	4.0	4.0	3.5	4.0	4.0
Moisture, max, wt %	3.0	3.0	3.0	3.0	3.0	3.0
LOI, max, wt %	12.0	6.0	6.0	5.0	6.0	6.0
Available alkalies, as Na_2O, max, wt %	1.5	1.5	2.0	1.5	2.0	2.0
Fineness, surface area, min, cm^2/cm^3	6500	6500	6500	3000 cm^2/g	6500	5000
Amount retained, 325M, max, wt %	--	--	--	12	12	22
Compressive strength of mortar cubes:						
Percent of control, 7 day, min	100	--	--	--	--	--
28 day, min	100	--	--	85	--	--
Pozzolanic activity index:						
Portland cement, 28 day, min, percent of control	85	75	75	--	85	70
Lime, 7 day, min, psi	800	900	900	--	1000	800
Water requirement, max, percent of control	105	103	103	103	--	--
Increase of drying shrinkage, mortar bars, 28 day, max, percent	0.03	--	--	--	--	--
Soundness, autoclave expansion or contraction, max, percent	0.05	0.50	0.50	--	--	--
Specific surface, max variation from average, percent	15	20	25	--	--	--
Specific gravity, max variation from average, percent	5	5	6	--	--	--
Air-entrainment agent requirement, max variation from average	20	--	--	--	--	--
Reactivity with cement alkalies:						
Mortar expansion, 14 day, max percent	0.020	--	--	--	--	--
Reduction of mortar expansion, 28 day, min percent	--	75	60	60	--	--

-- Dashes indicate either no specification or not available

ASTM C-618-68T:	Fly Ash and Raw or Calcined Natural Pozzolans for Use in Portland Cement
CRD-C-262-63:	Pozzolan for Use in Portland Cement Concrete
SS-P-570b:	Pozzolan for Use in Portland Cement Concrete
TVA G-30:	Fly Ash for Use as an Admixture in Concrete
Bu Rec 3172:	Cachuma Dam, 1950
Bu Rec DC-3413:	Davis Dam Spillway, 1951

Table 4-9. Comparisons of EEI Fly Ash Sample Data with Chemical Specifications

Specification	Analysis (Weight Percent)								Fly Ash not Conforming to Specifications			
	Al_2O_3 + SiO_2 + Fe_2O_3	SiO_2	Al_2O_3	MgO	SO_3	LOI	Moisture	Avail. Alk. as Na_2O	ASTM C-618-68T	CE CRD-C-262-63	Federal SS-P-570b; TVA G-30, Classes I & II	Bu Rec 3172, DC-3413
ASTM C-618-68T	70 min	--	--	--	5 max	12 max	3 max	1.5 max				
Corps of Engineers CRD-C-262-63	70 min	--	--	5 max	4 max	6 max	3 max	1.5 max				
Federal SS-P-570b, and TVA G-30 (Classes I & II)	75 min	--	--	5 max	4 max	6 max	3 max	2 max				
Bu Rec 3172, DC-3413 (Cachuma, Davis)	--	40 min	15 min	3 max	3.5 max	5 max	3 max	1.5 max				
Company Numbers												
26	87.4 94.0	52.1 50.1	32.0 33.2	0.4 0.5	0.6 0.4	2.1 1.9	0.3 0.3	0.8 0.9				
52	89.0 89.0 90.0	45.0 43.0 42.0	31.0 26.0 24.0	1.0 0.9 0.9	0.6 0.8 0.7	5.3 5.3 4.5	0.02 0.04 0.00	2.0 1.2 1.1	Alk.	Alk.		LOI, Alk. LOI
38	87.7	32.0	20.8	1.4	2.1	2.2	0	2.0	Alk.	Alk.		SiO_2, Alk.
17	83.0 83.0	39.6 42.6	23.9 23.8	1.2 1.1	1.5 1.9	5.9 6.0	-- 0.3	-- 0.3				SiO_2, LOI LOI
34	91.2	49.4	22.1	0.6	2.0	2.4	--	0.9				
39	84.8 93.4	37.0 45.7	24.4 29.8	0.7 0.8	0.9 0.5	10.7 8.0	0.1 0.1	0.7 0.6		LOI LOI	LOI LOI	SiO, LOI LOI
28	89.3	40.3	21.5	0.8	1.1	2.6	--	--				
14	91.5 89.4 88.8 87.7 86.2	41.4 43.1 38.0 45.0 42.3	19.8 23.9 14.6 2.14 20.7	0.8 0.9 0.7 0.8 0.7	0.6 1.5 0.1 0.5 0.5	3.8 3.5 -- 6.0 7.1	0.2 0.1 0.1 0.1 0.1	0.5 1.1 4.0 1.1 0.6	Alk.	Alk. LOI	Alk. LOI	Alk. SiO_2, Al_2O_3 LOI LOI
36	94.1	58.0	32.0	1.0	tr	0.6	--	0.3				
35 87.5	85.3 42.3	44.4 30.7	26.0 0.5	0.6 0.1	tr 5.7	6.4 0.2	-- 1.2	-- --		LOI	LOI	LOI LOI
31	88.6 86.3 87.0	39.7 44.7 49.2	17.4 21.9 25.5	0.2 0.8 0.2	2.5 2.0 1.8	6.4 6.4 6.0	0 0 0	1.3 1.2 1.3		LOI LOI	LOI LOI	SiO_2, LOI LOI LOI
9	90.5 92.4	42.0 44.6	20.8 35.4	0.6 0.8	0.3 0.6	3.3 5.1	-- --	2.1 --	Alk.	Alk.	Alk.	Alk. LOI
11	83.3 82.0 82.4 85.1	36.6 36.6 45.2 42.3	26.3 23.3 27.9 25.7	1.5 1.4 1.6 1.5	0.9 1.1 1.4 1.2	8.0 8.6 6.9 3.9	0.6 0.1 0.1 0.07	-- -- -- --		LOI LOI LOI	LOI LOI LOI	SiO_2, LOI SiO_2, LOI LOI
50	96.4	51.2	29.8	1.3	3.6	1.3	0.07	--				SO_3

Edison Electric Institute, "Fly Ash Utilization 1962," EEI Pub. No. 63-70, Sept., 1963.

Table 4-10. Comparison of OHIO Fly Ash Sample Data with Chemical Specifications

Specification		Analysis (Weight Percent)								Fly Ash not Conforming to Specifications			
		Al_2O_3 + SiO_2 + Fe_2O_3	SiO_2	Al_2O_3	MgO	SO_3	LOI	Moisture	Avail. Alk. as Na_2O	ASTM C-618-68T	CE CRD-C-262-63	Federal SS-P-570b; TVA G-30, Classes I & II	Bu Rec 3172, DC-3413
ASTM C-618-68T		70 min	--	--	--	5 max	12 max	3 max	1.5 max				
Corps of Engineers CRD-C-262-63		70 min	--	--	5 max	4 max	6 max	3 max	1.5 max				
Federal SS-P-570b, and TVA G-30 (Classes I & II)		75 min	--	--	5 max	4 max	6 max	3 max	2 max				
Bu Rec 3172, DC-3413 (Cachuma, Davis)		--	40 min	15 min	3 max	3.5 max	5 max	3 max	1.5 max				
Eng. Exp. Sta., Ohio St. Univ., Project EES-230, "The Suitability and Potential Uses of Locally Produced Fly Ash as an Admixture in Portland Cement Concrete," Dec. 1963.	Sample Numbers 1	89.77	43.25	21.93	0.76	1.21	3.23	0.25	0.71				
	2	92.76	49.70	22.85	1.34	0.49	0.24	0.17	0.53				
	3	--	--	--	--	--	--	--	--				
	4	90.81	42.74	23.15	0.54	0.49	4.83	0.16	0.59				
	5	87.37	44.13	24.67	0.77	1.28	6.61	0.49	0.66		LOI	LOI	LOI
	6	91.85	44.77	22.54	1.04	0.44	2.29	0.25	0.52				
	7	--	--	--	--	--	--	--	--				
	8	90.24	44.61	21.49	0.93	1.15	3.62	0.18	0.81				
	9	94.54	38.61	18.39	0.81	0.25	0.73	0.10	0.61				SiO_2
	10	91.70	49.08	33.43	0.70	0.35	4.63	0.17	0.75				
	11	91.60	46.91	24.33	0.68	1.22	2.95	0.52	1.93				
	12	90.83	45.61	26.13	0.84	0.16	5.09	0.11	0.82				LOI
	13	93.61	46.93	27.00	0.69	0.19	0.89	0.09	0.62				
	14	86.62	48.12	25.47	0.98	1.70	5.55	0.35	1.05				LOI
	15	84.50	41.21	19.63	0.77	0.51	9.03	0.25	0.63		LOI	LOI	LOI
	16	80.87	47.50	22.36	0.85	0.54	6.27	0.21	0.87		LOI	LOI	LOI
	17	92.19	43.03	19.15	0.67	1.16	3.54	0.44	0.77				
	18	92.33	35.78	19.30	0.52	0.90	3.12	0.16	0.41				SiO_2
	19	67.69	30.33	22.07	0.82	1.19	6.46	0.57	0.92	*	*	*	SiO_2, LOI
	20	77.36	40.99	20.45	0.98	1.14	16.82	0.79	0.73	LOI	LOI	LOI	LOI
	21	92.90	44.93	21.16	0.80	0.84	1.74	0.16	0.67				
	22	76.47	37.71	18.03	0.92	1.00	13.12	14.23	1.00	LOI, Mois.	LOI, Mois.	LOI, Mois.	LOI SiO_2, Mois.
	23	80.95	39.63	16.96	1.00	0.74	9.79	0.16	0.86		LOI	LOI	SiO_2, LOI
	24	90.28	43.85	19.83	0.73	0.29	5.40	0.16	0.54				LOI
	25	88.14	44.81	23.33	1.12	0.39	5.09	0.16	0.69				LOI
	26	84.24	41.71	21.64	1.03	0.59	8.25	0.16	0.51		LOI	LOI	LOI
	27	89.30	51.43	21.67	0.88	0.76	5.35	0.43	0.80				LOI
	28	91.13	51.06	21.85	1.02	0.98	2.53	0.40	0.78				
	29	77.33	23.64	18.43	0.74	3.39	3.95	0.50	0.80				SiO_2
	30	91.89	51.75	29.32	1.28	0.67	1.38	0.29	0.87				

Note: All are Ohio fly ashes.

* $Al_2O_3 + SiO_2 + Fe_2O_3$

Table 4-11. Comparisons of EEI Fly Ash Sample Data with Physical Specifications

Specification	Physical Property Requirements				Fly Ash not Conforming to Specifications					
	Specific Gravity	% Retained on 325M Sieve	Fineness-Surface Area, Minimum		ASTM C-618-68T	CE CRD-C-262-63	Federal SS-P-570b	Bu Rec 3172, DC-3413	TVA G-30 (Class I)	TVA G-30 (Class II)
			cm^2/cm^3	cm^2/g						
ASTM C-618-68T	--	--	6500	--						
Corps of Engineers CRD-C-262-63	--	--	6500	--						
Federal SS-P-570b	--	--	6500	--						
Bu Rec 3172, DC-3413	--	12	--	3000						
TVA G-30 (Class I)	--	12	6500	--						
TVA G-30 (Class II)	--	22	5000	--						
Company Numbers										
46	2.5	--	8320	3426						
	2.5	--	11,550	4603						
	2.5	--	6810	2764						
	2.5	--	12,700	5007						
	2.4	--	7800	3243						
	2.4	--	5700	2372	SA	SA	SA	SA	SA	
	2.4	--	8230	3427						
26	2.0	20	5700	2850	SA	SA	SA	SA, 325	SA, 325	
	2.2	17	6600	3000				325	325	
52	2.3	14.2	8830	3840				325	325	
	2.5	10.2	8850	3540						
	2.5	13.8	6800	2710				325	325	
17	2.4	15.6	8680	3620				325	325	
34	2.5	4.4	8880	3545						
39	2.5	14.3	8480	3390				325	325	
	2.4	18.1	10,200	4310						
28	2.4	11.4	6160	2571	SA	SA	SA	SA, 325	SA, 325	
14	2.5	24.1	4040	1616	SA	SA	SA	SA, 325	SA, 325	SA, 325
	2.5	10	7550	3020						
	2.3	51	3390	1472	SA	SA	SA	SA, 325	SA, 325	SA, 325
	2.3	18	6680	2904				325, SA	325	
	2.3	38.6	4720	2052	SA	SA	SA	SA, 325	SA, 325	SA, 325
36	2.3	18	5750	2500	SA	SA	SA	SA, 325	SA, 325	
35	2.2	21.3	4690	2127	SA	SA	SA	SA, 325	SA, 325	SA
	2.0	62.8	3280	1639	SA	SA	SA	SA, 325	SA, 325	SA, 325
51	2.4	42.1	4800	2000	SA	SA	SA	SA, 325	SA, 325	SA, 325
31	2.5	13.2	5270	2105	SA	SA	SA	SA, 325	SA, 325	
	2.3	12.8	4790	2516	SA	SA	SA	SA, 325	SA, 325	SA
	2.2	19.4	4950	2254	SA	SA	SA	SA, 325	SA, 325	SA
9	2.4	36.4	3360	1392	SA	SA	SA	SA, 325	SA, 325	SA, 325
	2.1	19	8080	3850				325	325	
11	2.5	27.4	--	--				325	325	325
	2.5	38.1	--	--				325	325	325
	2.4	11.4	--	--				325	325	
	2.5	7.4	4820	2326	SA	SA	SA	SA	SA	SA

Edison Electric Institute, "Fly Ash Utilization-1962," EEI Pub. No. 63-70, Sept., 1963.

-- Dashes indicate either no specification or not available

SA - Surface Area

Table 4-12. Comparisons of OHIO Fly Ash Sample Data with Physical Specifications

Specification		Physical Property Requirements				Fly Ash not Conforming to Specifications					
		Specific Gravity	% Retained on 325M Sieve	Fineness-Surface Area, Minimum		ASTM C-618-68T	CE CRD-C-262-63	Federal SS-P-570b	Bu Rec 3172, DC-3413	TVA G-30 (Class I)	TVA G-30 (Class II)
				cm^2/cm^3	cm^2/g						
ASTM C-618-68T		--	--	6500	--						
Corps of Engineers CRD-C-262-63		--	--	6500	--						
Federal SS-P-570b		--	--	6500	--						
Bu Rec 3172, DC-3413		--	12	--	3000						
TVA G-30 (Class I)		--	12	6500	--						
TVA G-30 (Class II)		--	22	5000	--						
Eng. Exp. Sta., Ohio State U., Project EES-230, "The Suitability and Potential Uses of Locally Produced Fly Ash as an Admixture in Portland Cement Concrete," Dec., 1963.	Sample Numbers 1	2.803	--	5400	1922	X	X	X	X	X	
	2	2.632	--	3920	1489	X	X	X	X	X	X
	3	--	--	--	--	--	--	--	--	--	--
	4	2.568	--	5790	2251	X	X	X	X	X	
	5	2.556	--	8700	3404						
	6	2.653	--	5540	2048	X	X	X	X	X	
	7	2.438	--	5800	2380	X	X	X	X	X	
	8	2.698	--	7120	2636						
	9	2.656	--	3520	1325	X	X	X	X	X	X
	10	2.193	--	6640	3025						
	11	2.493	--	8380	3361						
	12	2.346	--	9300	3955						
	13	2.345	--	5160	2201	X	X	X	X	X	
	14	2.543	--	14,500	5692						
	15	2.511	--	7740	3082						
	16	2.463	--	6410	2604	X	X	X	X	X	
	17	2.648	--	4740	1784	X	X	X	X	X	X
	18	2.860	--	5490	1918	X	X	X	X	X	
	19	2.517	--	14,100	5612						
	20	2.310	--	14,200	6149						
	21	2.637	--	5480	2493						
	22	2.388	--	8860	3712						
	23	2.437	--	7110	2925						
	24	2.524	--	6750	2664						
	25	2.474	--	7080	2863						
	26	2.580	--	4600	1781	X	X	X	X	X	X
	27	2.429	--	10,000	4128						
	28	2.418	--	5880	2435	X	X	X	X	X	
	29	2.870	--	5860	2043	X	X	X	X	X	
	30	2.340	--	7750	3309						

Note: All are Ohio fly ashes.

X indicates nonconformance

Table 4-13. Summary, Fly Ash Samples Conforming to Key Provision of Various Specifications for Use in Portland Cement Concrete

Pertinent Specifications	Fly Ash Samples, Percent Conforming to Key Provisions							
	Blaine Fineness, cm²/cm³ min, 144 Samples		LOI, % max, 165 Samples		Retained on 325M Sieve, % max, 151 Samples		(% + 325M) × (% LOI) ≲ 150, 149 Samples	All Criteria, % and (No. of Samples)
	6500	5000	12	6	12	20		
ASTM C-618-68T, Fly Ash and Raw or Calcined Natural Pozzolans for Use in Portland Cement Concrete	67.1	-	92.1	-	N.R.	N.R.	-	60.8 (128)
Proposed Amendment to ASTM C-618-68T	-	-	92.1	-	-	78.0	87.2	78.5 (149)
Federal Specification SS-P-570b; Corps of Engineers Specification CRD-C-262-63; American Petroleum Institute Standard 10A	67.1	-	-	71.1	N.R.	N.R.	-	46.1 (128)
Bureau of Reclamation Specifications 3172 and DC-3413; TVA Construction Specification G-30 (for Class I Ash)	67.1	-	-	71.0**	39.7	-	-	30.1 (113)
TVA Construction Specification G-30 (for Class II Ash)	-	90.9	-	71.0		83.3*		62.8 (113)

Note: Data on 168 fly ash samples were taken from:

(a) "Laboratory Investigation of 81 Fly Ashes," Concrete Laboratory Report No. C-680, Bureau of Reclamation, Denver, Colorado, 11 Sept. 1953.

(b) "Fly Ash Utilization - 1962," EEI Pub. No. 62-70, Fuel and Ash Handling Subcommittee of the Prime Movers Committee, Edison Electric Institute, N.Y., Sept. 1963.

(c) "Suitability of Ohio Fly Ashes in Portland Cement Concrete," EES-230, Arrand et al., Ohio State University Engineering Experiment Station, March 1968.

*This number based on specification requirement that less than 22 percent be retained on 325M.

**Assumes a 6% LOI requirement for Bu Rec. A 5% requirement would reduce this percentage from 71.0 to 56.4.

N.R. Not required.

- Not applicable.

specifications -- which is to say, those most often not met -- are LOI, Blaine fineness, and 325-mesh residue.

Chemical and physical property data for additional fly ash samples were compiled in the interest of increasing the statistical validity of the sampling. The data reported in Reference C-9 have been augmented by a later publication (Ref. C-123). A large, but rather old, compilation by the Bureau of Reclamation (Ref. B-7) was included, bringing the total number of fly ash analyses to 168. This entire body of sampling data is analyzed but not totally reproduced here. This sampling is believed to be representative of fly ash production between 1950 and 1962, and according to contacts made with numerous fly ash producers, brokers and the National Ash Association, no reason exists for believing that it differs significantly from current production.

Table 4-13 summarizes the manner in which the fly ashes of this sampling conforms to the key provisions of the specifications.* Clearly, ASTM C-618 is the least stringent of the specifications examined. Virtually the entire sampling met its 12 percent LOI requirement, and about 61 percent met both of its key provisions, LOI and fineness. (The proposed amendment to C-618 is discussed later in the text.) When the permissible LOI is decreased to 6 percent, only 71 percent of the sampling pass. Federal Specification SS-P-00570b and Corps of Engineers CRD-C-262-63 require 6 percent LOI, while retaining the same Blaine fineness as the ASTM requirement. Only 46 percent of the samples met both key criteria of these specifications. With the added provision that maximum retained on a 325-mesh sieve not exceed 12 percent, as in TVA G-30 (Class I), only 30 percent of the samples meet specifications. When TVA Class II ash (22 percent retained on a 325-mesh sieve) is considered, then 63 percent of the sampling comply with the specification. If the Blaine fineness requirement were deleted, as proposed by some users, the TVA Class I passing becomes 36 percent and the Class II would not be appreciably affected.

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* A minor liberty was taken with the data. Bureau of Reclamation Specifications 3172 and DC-3413, which are now historical documents, provide 5 percent maximum LOI. These have been combined in the table with TVA G-30 (Class I), which specifies 6 percent LOI. This was done to simplify the table, because their other key provisions are identical, and because the Bureau now honors the 6 percent LOI criterion. If the 5 percent criterion were invoked, the percent conforming, in the LOI column, would become 56.4.

Any of these specifications, if rigidly invoked and adhered to, would disqualify a substantial portion of production ash. The prima facie conclusion must be that current specifications inhibit the use of fly ash as a pozzolan in concrete if the potential concrete dealer or consumer is not motivated to use the ash. Methods by which the specifications are applied generally by those who want to use fly ash are discussed in the following paragraphs, and recommendations for specification changes are given in 4.3.3.6.

4.3.3.4 Specifications Versus Fly Ash Utilization

An assessment of the impact of existing specifications on the extent of fly ash utilization involves some vague parameters, and credible and meaningful information is not always available. User attitude is a consideration. Seldom will a user of a technically and economically useful raw material regard a specification for that material as rigid and inflexible, unless, of course, it suits some purpose to do so. Usually if sufficiently motivated, a user can circumvent a provision in a specification, either by allowing an exception, or by writing his own specification, or by altering a specification. These maneuvers, however, come after the raw material has been shown in plant or field trials to indeed meet his requirements. This suggests a basic inadequacy in the specifications.

A few notable examples of the attitudes of successful fly ash users toward specifications have appeared in the technical press and/or were developed in this study. Robert W. Cannon (Ref. C-55) of TVA has stated:

> "Present TVA policy is to use the source of fly ash which offers the greatest economy in the concrete for each particular construction project regardless of whether the fly ash meets Federal and ASTM specifications."

A similar view was stated in an interview with a producer of concrete block:[*]

> "Requirements such as LOI limits, fineness, or anything else, are not specified to the fly ash suppliers. The fly ash delivered must be good for concrete block, and it is up to the supplier to provide the required fly ash. So far, there have been no problems with this procedure."

A prominent concrete technologist stated:[*]

> "For some years it has been demonstrated that fly ashes which will not meet standard specifications, when properly proportioned with cement, aggregate and water, can produce concrete of equal strengths to concrete without fly ash. In effect, any given concrete requirement can be met with most fly ashes as long as the ash characteristics are known."

Finally, the views of a researcher,[*] as stated in a personal interview:

> "Specifications are not an inhibition of fly ash utilization in any way. Existing specifications are irrelevant but not inhibiting. Some people use specifications as an excuse; if the specifications were changed, they would find another excuse. Specifications never prevented anyone from using fly ash if they truly wanted to do so."

Thus it is seen that fly ashes which do not conform to specifications can and are being used successfully. However, this is not always easy to do, for as the properties of an ash deviate from a norm, adjustments in concrete batching must be made. This, of course, requires research and development. The successful use of nonspecification fly ash seems to hinge on the motivation of the user. Those users who are not motivated to improvise can contend with some justice that a nonspecification ash is unusable. If this is the interpretation, then the specifications are in fact inhibitory. If a user wants to be inhibited in his use of fly ash by specification, it can easily be arranged. Conversely, if a user really wants to use fly ash, then, for most fly ash produced, the existing specifications become meaningless.

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[*] Personal communications, 1971.

4.3.3.5 Adequacy of Existing Specifications

Some doubt was cast in the previous section on the adequacy of the existing fly ash specifications. The fact that certain nonspecification ashes can be made to perform satisfactorily in concrete mixes suggests that the specifications indeed may not be all that they could be. As shown, fly ash specifications are based on chemical analyses and a few physical properties. To date there has been no particularly convincing demonstration that these particular qualities of an ash correlate very strongly with its performance in a concrete mix. In fact, there is evidence that a once highly regarded property, the Blaine fineness of an ash, correlates poorly.

The questionable adequacy of the specifications has received and is receiving the attention of numerous scientists and technologists in the field. The views of Snyder (Ref. F-40) are deemed worthy of quotation at some length:

> "In some cases, the specifications apparently have been derived from continued satisfactory performance of the fly ash from a single producer, or a few producers, and are essentially a description of those fly ashes. In either case, because the specifications are primarily based on experience with a limited number of fly ashes, it is possible on the one hand, to find fly ashes which meet a given specification but do not result in acceptable products, and on the other hand, to find fly ashes which do not meet the specification but do result in acceptable products.
>
> "Although it is possible for producers and consumers of fly ash to reach agreement concerning the suitability of a given fly ash for a given use on the basis of present specifications, neither party's interests are fully served by present specifications. From the viewpont of the purchaser, there is an unknown degree of risk that a fly ash which meets specifications may not prove to be satisfactory in service. From the viewpoint of the producer, the specifications may well be more restrictive than is warranted, leading to the rejection of fly ash that would have performed satisfactorily in service. From the viewpoint of a person involved in research on the characterization of fly ash, the specifications are unsatisfactory because there is considerable question about whether some of the characteristics being measured and specified really have any significance with respect to the characteristics of the final product."

A different viewpoint is provided by Morrison (Ref. F-76) of American Electric Power Service Corporation, a producer of quality ash:

> "There are not too many technical problems connected with using fly ash in Portland cement concrete structures. There is, however, the problem of getting state highway departments, federal agencies, contractors, and some large companies to adopt existing fly ash specifications. Most of us who have spent several years promoting fly ash believe that resistance to change, or complacency, is the largest stumbling block in ash promotion. Very few individuals find fault with the merits of using fly ash or adopting ash specifications."

Other investigators have advocated dual specifications, based both on measured properties of fly ash and on its performance in concrete batches. This approach would be the logical outgrowth of the empirical procedures of some users who simply "try it and see if it works." Presumably, the properties of a satisfactory fly ash concrete would form the basis of the performance specification. This rather cumbersome system would be superior in terms of relevance of testing to the present system.

A developing body of opinion has come to believe that the proper use of a combination of properties currently covered by specifications could add relevance to the specifications. Under ASTM committee scrutiny at the present is a concept wherein the product relationship between LOI and 325-mesh-sieve residue, both in weight percent, should not exceed 150, with the added provisions that LOI and the 325 residue individually not exceed 12 and 20 weight percent, respectively (see Table 4-13). An excerpt from ASTM committee correspondence, provided by one if its members* and based on lengthy statistical analyses, lends considerable credence to the validity of the concept:

> "The present existence of irrelevant specifications, specifically the Blaine fineness requirement, is the major deterrent to fly ash use in concrete. Significant correlation coefficients are generally developed between the sieve fineness or the product of LOI times 325 sieve fineness and performance of concrete containing fly ash (including water requirement, strength of mortar, strength of concrete, and air-entraining agent demand). The fact

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*Personal Communication, 1971

> that the 325 sieve fineness and the LOI times 325 sieve fineness often gives the highest correlation coefficient is indicative of a relatively high, close correlation between these factors and the performance of concrete containing fly ash. No correlation is evident between the Blaine fineness and the overall performance value. In all of the areas where there is some evidence of correlation between the performance test and the Blaine fineness, the correlations obtained by the use of other variables are more significant."

It appears that the committee is moving to abolish the Blaine fineness requirement of ASTM C-618 altogether. According to numerous sources, the move is developing considerable support throughout the industry. If indeed the product parameter is accepted as a sensitive indicator of fly ash performance in concrete, the industry would have achieved a valuable gain in relevance as well as simplifying the acceptance testing required for fly ash. The Blaine test is relatively complex compared to LOI and 325-residue tests.

It is shown in Table 4-13 that the conformance of well over one hundred samples to ASTM C-168 is increased from 61 to 79 percent by deleting the Blaine fineness requirement while invoking the LOI-fineness product limit. This may not be indicative of potential usage, however (See 4.3.3.6).

As to the future of fly ash specifications, a quotation by Edward J. Hyland (Ref. C-13) of the Chicago Fly Ash Company seems appropriate:

> "Organizations such as The American Society for Testing and Materials, The American Concrete Institute, and The Highway Research Board write specifications and recommended practices under which all of us are able to sell fly ash in the ready-mixed concrete market. Up to now, those organizations have respected the legitimate rights of all fly ash suppliers and recognize the advantages fly ash imparts to concrete because some fly ash suppliers were willing to invest their time and money in representing an industry.
>
> However, all of us who are interested in furthering the use of fly ash in ready-mixed concrete must join in the effort to insure that proper documents are written which will permit the proper use of fly ash. Our objective in all our activities including our technical society undertakings should be that fly ash sould be fairly treated -- not afforded an unfair advantage over anyone but also not legislated out of its legitimate market by groups hostile to us."

4.3.3.6 Proposed Specification Modifications

The arguments for specification changes are well founded (see Section 4.3). The proposed modifications by ASTM and the federal specifications attest to the industrial awareness and dissatisfaction with existing specifications. Crucial to the entire argument for such changes is not only the irrelevance of existing specifications, but also the relevance of the new specifications. For example, the ASTM data accumulated to correlate fly ash parameters to concrete properties have demonstrated the statistical relevance of the multiple factor of percent LOI times percent retained on a 325-mesh sieve. (Ref. C-129) Furthermore, these data have demonstrated the tremendous superiority of this multiple factor to existing specification parameters. The basis for this new parameter, however, is solely empirical and the very limited number of fly ash samples studied cannot be considered statistically representative of "fly ashes".

The proposed ASTM modification would help solve part of the problems generated by the existing specification, i.e., include fly ash which does not now meet specifications but can produce an acceptable product (see Table 4-13). However, by so doing, it does not alleviate the problem of fly ash that is acceptable according to specification but which does not produce an acceptable product, nor does it necessarily include all fly ashes which can produce an acceptable product. Although these proposed modifications provide a distinct advantage over existing specifications, it is apparent by their deficiencies that the multiple factor is still not the sole nor the correct parameter by which fly ash should be judged. The basic work which would unequivocally define such a parameter has not yet been conducted.

A recent research study conducted at Iowa State University (Ref. B-21) on the pozzolanic reaction of synthetic fly ash most closely satisfies the type of study required to define the relevance of various physical and chemical parameters of fly ash. This study found that the parameter which had the most influence on pozzolanic activity of fly ash was the extent of strain in the glass particles which make up the finer fractions of the fly ash. The finer fly ash was a more effective pozzolan than the coarser fly ash but this behavior was explained by the increased quantity of glass particles appearing in the finer fraction. (The chemical make-up of the fly ash also had an effect on pozzolanic property but this effect was small relative to the quantity and quality of glass particles.) The strain in the glass was correlated with the thermal history in the snythesis of the fly ash and may explain why the multiple factor is a more relevant parameter than others since both fineness and residual carbon are functions of thermal history.

Nevertheless, the Iowa State study has indicated that neither fly ash fineness (which could be a function of coal type or pulverizer equipment as well as thermal history of the fly ash) nor residual carbon (which could be a function of pulverizer equipment and combustion oxygen ratio as well as thermal history) are direct parameters, but, in fact, are secondary parameters. In addition, there is no standard technique which could directly test for the extent of strain in the glass particles. Furthermore, it is now premature to consider such a test until more extensive research has been conducted to verify the observations of this study on power plant fly ash.

The Iowa State University study suggests that the minimum requirements on the oxides of silicon, aluminum and iron are meaningless and serve only to exclude arbitrarily the lignite ashes. The acceptability of lignite fly ash as a pozzolan has been more than adequately verified by studies conducted at the University of North Dakota (Ref. A-1). Exceptions to the irrelevance of limitations on chemical constituents are those on sulfur dioxide, magnesium oxide and alkalies, which are unquestionably detrimental in concrete and mortar.

Existing specifications are restrictive primarily with respect to residual carbon and fineness (see Table 4-16). While the proposed ASTM modifications will be partially effective in relieving these restrictions and increasing the relative amount of fly ash acceptable by specifications, it does not necessarily indicate that the amount of fly ash actually accepted for use in concrete will be increased. By broadening the range of acceptable fly ash, the specifications become less effective in defining the ability of the fly ash to be used in a standard manner to give predictable results. As an example, users commonly impose a 6 percent LOI restriction on the ASTM specification (ASTM C-618 limits LOI to 12 percent) because of the increasing difficulty and expense in control of air entrainment as residual carbon increases beyond 6 percent. The requirement, then is for broad specifications which classify fly ash in such a fashion that a standard technique for each class can result in predictable performance.

The specifications on fly ash as defined by TVA provide a suitable example for the type of classification that is required (Refs. F-80, F-81 and Appendix H). In this case fly ash is classified by fineness, in which Class I represents that ash in which less than 12 percent is retained on a 325 mesh sieve. For Classes II and III, ashes up to 22 percent and 32 percent, respectively, may be retained on a 325-mesh sieve. In Class III, coarser fly ash is accepted and is used successfully although not allowed by any other specification. Furthermore, the use of coarse fly ash is done in a standard manner and does produce predictable results. The TVA recognition of the coarser fractions as a mineral filler allows suitable adjustment in sand and cement so that virtually identical results can be obtained with each class of fly ash.

It is conceived that this classification concept can be extended to other relevant parameters such as residual carbon (LOI) and pozzolanic activity index or any other parameter that is found to be truly relevant to the use of fly ash as a pozzolan.

The consequence of this proposed change is immediately apparent. Often, more than half the cost of fly ash is transportation. Many times heavy transportation charges are incurred because of the absence of a local source of acceptable fly ash (by present specifications). With a classification system of specifications, such local fly ash may then be acceptable and significant savings can be made and a total improvement in the economics of using fly ash may result.

4.3.4 Fly Ash for Use in the Manufacture of Portland Cement and Portland Cement Concrete Products

As mentioned earlier, there are specifications for concrete products and cement in which fly ash is or may be used. Typical of these (Ref. F-6) are:

a. ASTM C-90, Hollow Load-Bearing Concrete Masonry Units
b. ASTM C-129, Hollow Non-Load-Bearing Concrete Masonry Units
c. ASTM C-145, Solid Load-Bearing Concrete Masonry Units
d. ASTM C-139, Concrete Masonry Units for Construction of Catch Basins and Manholes
e. ASTM C-55, Concrete Building Brick

These specifications simply state that if fly ash is used, it must conform to the provisions of the current specification governing the use of fly ash in concrete, which now is C-618.

Some product specifications are more informal. For example, ASTM C-465, "Processing Additions for Use in the Manufacture of Portland Cement," (Ref. F-18) is concerned with materials which may be interground with cement clinker, of which fly ash may be one. It requires that the addition "be classed as not harmful," and details various tests of cements containing additions, the results to be compared with those of the same tests on control specimens.

ASTM C-595, "Blended Hydraulic Cements," (Ref. F-4) is slightly more specific. It provides for portland-pozzolan cements, among others, and imposes certain requirements on the pozzolans. Fly ash is identified as a potentially useful pozzolan. According to C-595, the pozzolan must have a pozzolanic strength with lime of 800 psi minimum, and a 325-mesh-sieve residue of 12 percent maximum. Most fly ashes will meet the strength requirement; the fineness requirement imposes restrictions on a substantial portion of production ashes.

In addition to the requirements of specifications, good practice, developed through experience, has led to certain informal requirements imposed by individual producers. For example, Type II cement (moderate sulfate resistance and moderate heat of hydration) has limitations imposed on the Al_2O_3 and Fe_2O_3 contents. These oxides in excessive amounts cause the development of undesirable phases in the cement. A fly ash containing large amounts of these oxides, used as kiln feed for the cement, could be classed as a harmful addition according to ASTM C-465. Nevertheless, good practice dictates that a fly ash used in this manner not contain more Al_2O_3 or Fe_2O_3 than is allowed by ASTM C-150. Many fly ashes fail to meet one or both of these criteria, and probably would be considered an unsuitable raw material for kiln feed for Type II cement. Ashes interground with cement are not under this constraint, since the undesirable phases are generated only at high temperatures.

4.3.5 Fly Ash for Use in Products Other Than Portland Cement Concrete

The specification literature on fly ash for use in products other than concrete is meager. Only two such ASTM specifications were located. The more pertinent is ASTM C-593-66T, "Fly Ash and Other Pozzolans for Use With Lime," (Ref. F-2). Compared to C-618, the requirements of C-593 are not at all rigorous. It provides for a maximum water soluble fraction of 10 weight percent and a maximum residue on a 200-mesh sieve of 30 percent. Also, the strength requirement for a lime-pozzolan mortar is less than that required by C-618. Virtually all fly ashes (probably upwards of 90 percent) will meet specification C-593.

The pertinence of C-593 lies chiefly in its applicability to the use of fly ash in highway base course construction. This utilization is discussed further in Section 4.4.2.2. State highway departments who use lime-fly ash aggregate or lime-fly ash soil construction generally require that the fly ash conform to C-593. Occasionally additional provisions are stated, such as limits on fly ash content of the mix, e.g., 8 to 30 percent; 10 percent minimum; and 9 to 15 percent. These generally are dictated by local conditions and construction practices, and do not seem to inhibit the use of fly ash. The only limitations on fly ash that were stated for use in pozzolan base courses are that its carbon content and 325-mesh sieve residue should not exceed 15 and 50 weight percent, respectively.*

ASTM specification D 242-64 (Ref. F-3) covers mineral filler for bituminous paving mixtures. Filler generally constitutes 3 to 6 percent of these mixtures. The only requirements of D 242 are that the filler be dry, free of lumps, and that 70 to 100 percent pass a 200-mesh sieve. Any fly ash, given reasonable handling, will meet this specification.

Fly ash is used in certain processes based on sintering; for example, in the manufacture of brick and lightweight aggregate (see Section 4.4.2.4 and Section 4.4.2.5). There are no specifications on fly ash for use in these applications. ASTM C-330 (Ref. F-7) and ASTM C-331 (Ref. F-5) mention fly ash as a possible raw material for lightweight aggregates, but impose no inhibiting requirements on the raw materials.

The manufacturers of sintered products have placed very specific requirements on raw materials properties. First, the material must be capable of being formed into some useful shape. Then it must sinter in some economic operation to develop the required strength and structure. In the case of brick manufacture, a new raw material must be compatible with other batch constituents. Also, it must not create soluble phases in the finished brick, which would cause efflorescence. For lightweight aggregate, the Fe_2O_3 content of the fly ash should be moderate in the interest of lightness, and in order that iron in the aggregate not stain the concrete. Also, common practice (largely developmental) requires that fly ash for lightweight aggregate contain approximately 5 percent carbon as a fuel in order to satisfy ASTM C-330 and 331.

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*Personal Communication, 1971.

4.4 FLY ASH CONCRETE - ADVANCED TECHNOLOGY

The technology related to the utilization of fly ash concrete is discussed separately in consideration of the large potential market for this utilization, the many inhibitions to its use, and the reasonable potential that exists to remove the inhibitions through technological advancements*. These inhibitions can be attributed to the misunderstanding of the technology by fly ash producers and potential users alike, and a lack of relevancy of existing specifications to the true potential of the various grades of fly ash produced today. It is recognized that this technology is well understood by a few individuals in the concrete industry, from whom much of these data were obtained; however, it is believed that this technology has not reached the thousands of individuals who are to be involved if large sums of fly ash are to be consumed as an admixture in concrete.

The utilization of fly ash is possible only because suitable technology has been developed. Representatives of the fly ash industry generally do not see technology as an inhibiting factor to the use of fly ash; however, this study has revealed that in its interactions with other factors, technology does contribute to the inhibition of fly ash use. Inhibiting technical factors are unique to the product and to the market in which it must compete. Besides the factors associated with technologies that have not fully evolved, the interactions of technology with economics, fly ash quality, specifications, and user knowledge, acceptance and confidence have all had an inhibiting effect on the use of fly ash. Moreover, technology has the potential capability to alleviate many of the inhibiting factors through continued development. However, in nearly every application of fly ash, the advancement of the technology has not reached an optimum level of functional use.

The earliest use of fly ash in the United States was made more than 30 years ago as a cement substitute in portland cement concrete. This use of

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*This section supplements 4.2.1.1 which pertains to the current utilization of fly ash as a concrete admixture.

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fly ash has been the most important advancement during the development of the fly ash industry and presently accounts for nearly one-third of the total fly ash used for economic purposes. The early development of a fly ash concrete technology is easily understood. It chemically and physically resembles natural pozzolans and it is reasonable to expect that it would be used for this purpose. However, as a pozzolanic material it is superior to natural pozzolans; furthermore, it serves in a secondary role as a filler material.

4.4.1 Advantages and Disadvantages

Significant advantages can be realized in the properties of concrete containing fly ash (Refs: A-9, B-15, and B-19). With fly ash, concrete can be designed for very high strengths which exhibit a smaller variability of strength due to the pozzolanic reaction with the free lime in portland cement. This reaction takes place over a long period of time and shows a continued strengthening after portland cement concretes have fully matured. However, when fly ash is improperly used in concrete, this slower reaction can produce lower early strength and retarded setting may occur in the lean concrete mixes.

As a mineral filler, fly ash replaces water, fine aggregate and cement. In this role fly ash reduces the water requirement (especially in conjunction with a wetting agent) and improves workability; decreases particle segregation and bleeding; reduces water permeability which in turn improves resistance to sulfate attack and improves surface wear resistance. The slower reaction of fly ash especially in lean mixes, reduces the heat of hydration and in conjunction with water replacement, reduces shrinkage. Its reaction with lime reduces lime leaching and scumming and neutralizes alkali-aggregate reactions. However, its small spherical particles which improve workability also increase slump, and the retention of adequate air entrainment for durability requires the use of suitable chemical admixtures.

Although the advantages of fly ash concrete far outweigh the disadvantages, adverse experiences by concrete users have severely inhibited the use of fly ash in concrete in certain regions. The technology required to circumvent these less desirable property characteristics has been developed but is not being widely used.

4.4.2 Substitution Versus Ingredient

A distinctive point in the evolution of fly ash concrete was its recognition as a technology apart from portland cement concrete technology. The early uses of fly ash in concrete were made as a partial cement substitute; fly ash is still being used in this manner even by several large users of concrete. Substitution is made on a 1:1 volume or weight basis. However, advancements in the technology have recognized fly ash as a discrete ingredient in concrete. Such concrete, although similar to portland cement concrete, has distinctively different properties. Depending on the specific use of the concrete, properties can usually be tailored to an advantage over those of portland cement concrete. In contrast, however, concrete in which fly ash is used as a cement substitute cannot be tailored to compensate for those less desirable properties given to the concrete by the fly ash. In some specific applications, this is adequate since fly ash used in concrete within certain limits (based on actual practice data) provides advantages without developing significant structural design variations from portland cement concrete. This, however, is not taking advantage of the design efficiencies that are possible through the use of fly ash.

The main pioneers of this advanced technology are the Chicago Fly Ash Company and TVA (Refs. C-56 and C-55). In both cases, this newer technology is described in terms of proportioning of the concrete mix.

An example of the fly ash technology established by Lovewell and Hyland of the Chicago Fly Ash Company (and published in the Concrete Industries Yearbook, 1970) is shown in Fig. 4-10 and demonstrates the structural advantages that can be gained by using fly ash as a concrete ingredient. This figure, combined with other Yearbook data, provides suggested trial mixes

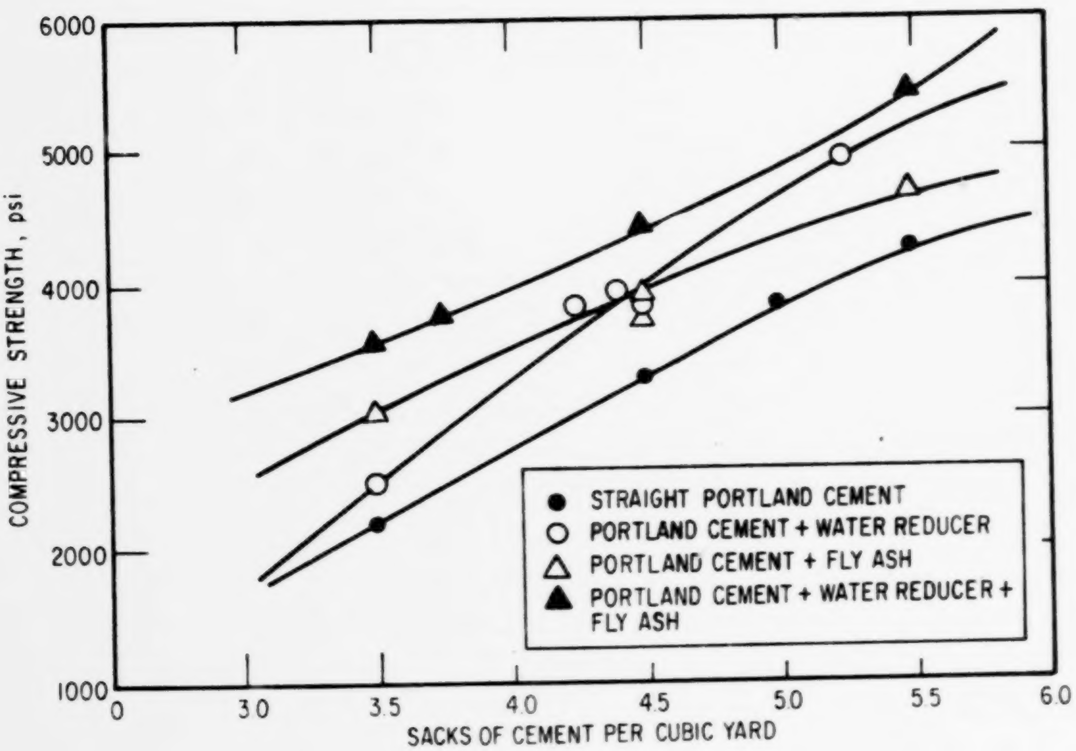


Fig. 4-10. Compressive Strength of Various Concrete Mixtures
Age at Test - 28 days

which shows that comparable 28-day strengths can be attained by using less cement and adding fly ash in a volume proportion of 2 fly ash added to 1 cement portion removed (suitable fine aggregate adjustments were also made). An explicit example can be made at a compressive strength of 4000 psi where a concrete containing 4 sacks of cement and 100 pounds of fly ash has comparable 28-day strength to a concrete containing 4. 75 sacks of cement (both concretes contain water reducing agents).

The TVA has interest in concrete in a broad range of uses including both structural and mass fill concrete. The proportioning schemes they have developed use fly ash effectively in each of their applications. The variability that is possible through appropriate proportioning of concrete ingredients has permitted the design of concretes which maximize the advantages that fly ash provides while minimizing the disadvantages. For example, by replacing more fly ash than cement removed from the concrete mix allows the fly ash to be used not only as a pozzolan to replace cementitious materials but also to replace sand and water as mineral filler. With fly ash serving as a mineral filler, non-air-entrained concrete has greater early strengths (1-3 days) than comparable straight portland cement concrete, and air-entrained has nearly the same strength as comparable straight portland cement concrete, thereby eliminating the low early strengths often associated with fly ash concrete by the substitution technology, and allows form removal on the same schedule as with straight portland cement concrete. The recognition of fly ash as a mineral filler has permitted TVA to use lower quality fly ash than otherwise allowed because the coarse fraction replaces fine aggregate (see 4. 3. 3. 6).

The example given in Fig. 4-11 illustrates the technology practiced by Cannon of TVA. The two major factors affecting strength are simultaneously plotted: the water-to-cementitious material ratio, and the fly ash-to-cement ratio. The third variable is the quantity of cement, plotted in dashed lines as sacks of cement per yard of concrete. The solid lines represent the measured compressive strength after 28 days for the given relationships. A lateral

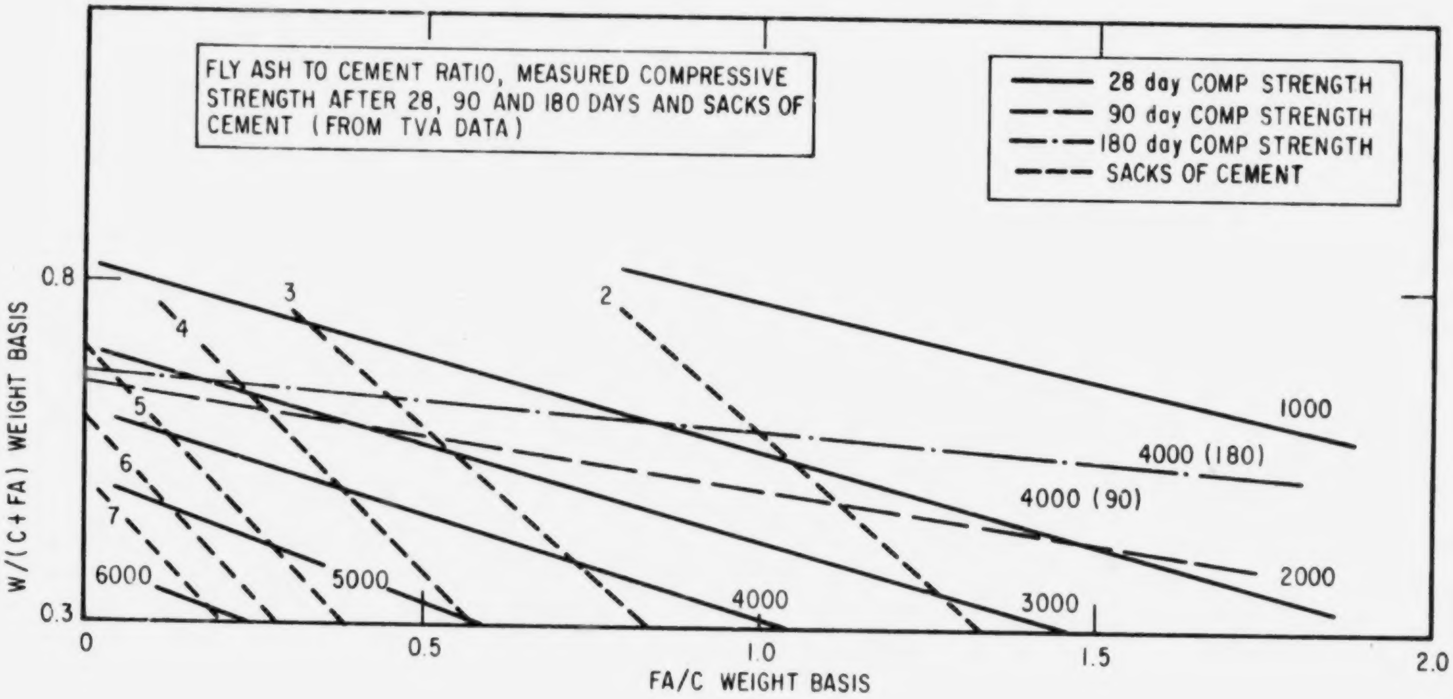


Fig. 4-11. Proportioning and Curing Time Effects on Compressive Strength

translation of cement quantity on the coordinates will cause a vertical displacement on the strengths. The effect of the pozzolanic reaction is shown for the 4000 psi strengths after 90 and 180 days, where the importance of high concentrations of fly ash for high strength development over long time periods can be readily seen. As an example, a concrete with a W/(C+FA) ratio of 0.5 and a FA/C ratio of 1.0 has a 28-day design strength of 2400 psi. This same concrete could be used for a 90 day design strength of 4000 psi or a 180-day design strength of 4900 psi. The curing conditions required for 90 and 180 day design concretes are no different than those for standard 28-day design concretes.

As another example, a 4000-psi, 28-day compressive strength concrete is taken at 4 sacks of cement. In this case the W/(C+FA) ratio is 0.5 and the FA/C ratio is 0.38. If construction considerations allow, a 90-day design strength permits a concrete mix with a W/(C+FA) ratio again of 0.5, a FA/C ratio of 1.0 and only 2.25 sacks of cement are necessary. Further, if 180-day design strengths can be permitted, 4000 psi can be obtained at a W/(C+FA) ratio of 0.5, a FA/C ratio of 2.0 and only 1.25 sacks of cement are required.

The choice of concrete cure time should be based on the economics involved with construction. Since the savings in materials from the use of fly ash is often small relative to the cost of placing the concrete, the design conditions should be dependent upon the requirements of construction. However, the state-of-the-art in concrete construction requires design compressive strengths of 28 days and does not include an optimal cure time in the total economics. A cure time of 28 days represents that point at which portland cement concrete will attain up to approximately 90 percent of its ultimate strength and is considered representative of the true strength of the concrete. However, in concrete containing fly ash, 28 day cure times are arbitrary and meaningless since the strength tested at that time does not represent the ultimate strength of the concrete when fully cured. While the concept of 28-day design strengths largely dominate the concrete construction industry, there are few examples that can be cited in which structures under construction will experience their design loads in 28 days. Until the concrete construction industry becomes aware of the increased latitude in concrete mix design that is offered by a technology using fly ash in an effective, economical manner, an inhibition to the use of fly ash in concrete will persist.

The continued development and acceptance of properly proportioned fly ash in concrete is likely to provide the basis for renewed interest in fly ash as a concrete ingredient. When the users of concrete become more fully aware of the range of properties that properly proportioned fly ash concrete offers, their reluctance to use fly ash in concrete (based on the performance of inadequate cement-substitution technology) will diminish and an increase in the use of fly ash in concrete may be expected.

4.4.3 Quality-Specification Relationship

Neither the quality of the fly ash nor the arbitrary restrictions of specifications has seriously limited the use of fly ash in concrete, thus far; however, further development of its potential will be inhibited by their interrelationship. Elimination of this potential inhibition would require either improvement in the quality of the fly ash being produced, changes in specifications to increase the acceptability of fly ash, or both. It is not the intent to discuss here the quality of the fly ash nor specifications but to discuss the role of technology in their interrelationship. As previously stated, virtually all fly ash can be used successfully in concrete. The role of specifications is to allow fly ash to be used in a standard manner to produce predictable properties. The role of technology then should be to provide the basis on which a series of specifications may be established which would permit all fly ashes to be used in one of a set of standard ways to give a specific set of results. Unfortunately, the fundamental understanding of the pozzolanic reaction which would permit this to be done has not been available. A significant insight into the understanding was recently acquired from work conducted at Iowa State University on synthetic fly ash (see Section 4.3.3.6 and Ref. B-21). The various physical and chemical parameters which are normally used to assess the quality of fly ash were investigated relative to their pozzolanic reaction. The chemical content and fineness are usually considered the most significant parameters for fly ash quality and are the parameters found most restrictive in specifications. However, the direct correlations between these parameters and the performance of the fly ash has never been adequately obtained. The data have suggested that these parameters are not direct parameters and that the pozzolanic activity of fly ash is dependent upon some yet unidentified variable. The Iowa State study confirms this contention by identifying such a variable. Whereas the chemical constituents of the fly ash affected pozzolanic reaction and the reactivity increased as expected with increased fineness, the most sensitive parameter was the glass content of the ash. Moreover, the variable was seen not to be glass content per se, but the extent of strain existing within the glass as a consequence of its thermal history. The most reactive fly ash was that which was subjected to a rapid thermal quench; slowly cooled fly ash was totally unreactive. From this study it may be deduced that the major parameters affecting the quality of the fly ash are the boiler conditions for producing the ash and the rate at which the ash is cooled. This study indicates that the criteria presently used for qualifying fly ash for concrete use is somewhat irrelevant. Furthermore, the present technique for establishing specifications does not appear capable of defining the suitability of fly ash for this purpose. The Iowa State study does not provide sufficient basis for establishing a new set of specifications, but it does reveal an apparent impertinence of present specifications.

The technical inhibitions that contribute to the limited use of fly ash in concrete as discussed in the previous paragraphs have been directed primarily toward on-site concrete. In contrast, in-plant production of concrete products such as block and precast/prestressed concrete has not been affected by inhibiting factors toward fly ash use. Manufacturers of in-plant concrete products have an advantage of pre-testing their product before sale, and further, they are subject to far fewer controls.

Concrete block are now being made by many manufacturers in which large quantities of fly ash are being used. Technical limitations, if they exist, are not apparent.

4.5 FLY ASH IN PAVING

Many components of modern roads have contained fly ash on an experimental basis, and in a few instances fly ash is used routinely. It has been demonstrated that with proper batching and placing, fly ash wear courses, base courses, shoulders and structural fill possessing considerable technical merit can be laid. In view of the vast tonnage of materials used in the paving of roads, runways and parking surfaces, it is apparent that this type of construction offers a large potential outlet for fly ash.

The following conclusions concerning the utilization of fly ash in this type of construction can be made as a result of this survey:

1. The widespread potential utilization of fly ash in wear course portland cement concrete is low. Its potential as a constituent of base courses is large, but may require government assistance. As a fill material in bituminous concrete, its use is good but will not consume large amounts. Its potential utilization as a structural fill is small, although it can consume large sums in isolated cases only.
2. Most state highway departments are reticent about the reasons for their limited use of fly ash.
3. Existing specifications do not seem to limit or inhibit the use of fly ash in road building programs.
4. Most highway departments exhibit little interest in the application of present or developing technologies leading to more widespread use of fly ash.
5. Today's limited success in local areas is due to the untiring efforts of only a few individuals.
6. Badly needed are programs of education and promotion to demonstrate the technical and economic merits of effective fly ash utilization in roadway programs.
7. Technical and marketing surveys of potential utilization of fly ash as a base course material are recommended (see Section 1.4.1).

4.5.1 Pavement Design

The design of pavement to support a 700,000-pound airplane or withstand

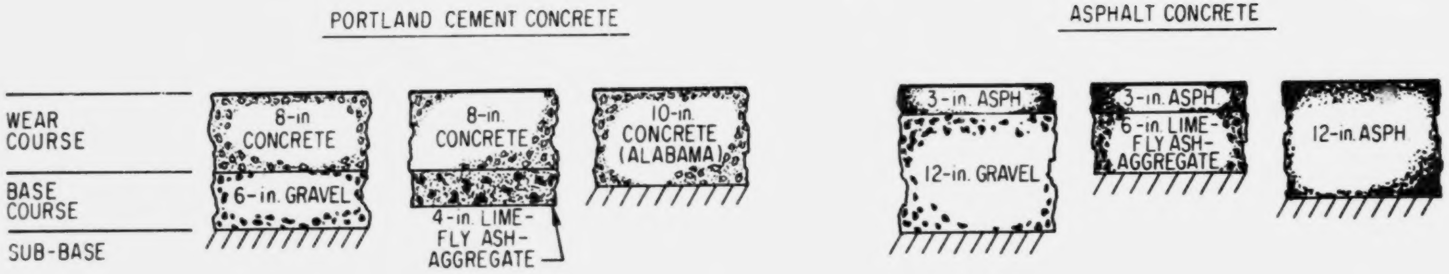
1,000,000 passes of a 20,000-pound axle load is a complex matter. Most highway pavements have a few features in common. Starting with a prepared subgrade, a base course generally, but not always, is laid. Its chief function is to distribute the applied load over a large area of the subgrade. The base course may consist of 6 to 12 inches of crushed stone or gravel; it may consist of 4 to 8 inches of lime-fly ash-aggregate or lime-cement-fly ash-aggregate; or it may consist of several inches of a bituminous concrete composition or a low-grade portland cement concrete. Base courses are not suited for highway wear and tear; therefore, they are covered by a wear course designed to resist the friction and shear forces imposed by traffic. This layer is usually 8 inches or so of portland cement concrete or 2 to 4 inches of asphalt.

Airport design presents different problems. Wheel loads may be upwards of 100,000 pounds, but only 20,000 to 40,000 passes may be considered to be the life of the pavement (Ref. H-14). The major design difference usually is that the airport section is thicker than a first-class highway section. However, materials and construction principles are generally similar.

Several highway and recent airport designs are presented in Figs. 4-12 and 4-13 which show some typical pavement components which do or could contain fly ash. Although fly ash is not a major constituent, it is seen that significant quantities would be consumed were it widely employed.

4.5.2 Fly Ash Utilization in State Highway Programs

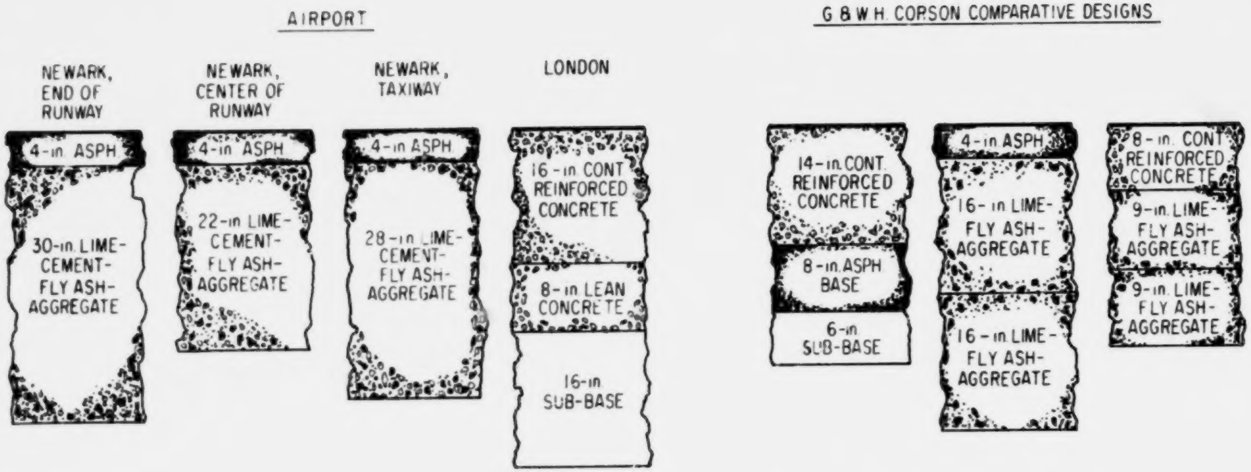
A short survey was conducted to estimate the extent of fly ash usage in present highway construction. Contacts were made with numerous trade associations and government agencies which included, among others, the U. S. Corps of Engineers, the Bureau of Reclamation, the Highway Research Board, the National Ash Association, the American Concrete Institute, the Portland Cement Association, and several paving associations.


PORTLAND CEMENT CONCRETE
ASPHALT CONCRETE
WEAR COURSE
BASE COURSE
SUB-BASE
8-in CONCRETE
6-in. GRAVEL
8-in. CONCRETE
4-in. LIME-FLY ASH-AGGREGATE
10-in. CONCRETE (ALABAMA)
3-in. ASPH.
12-in. GRAVEL
3-in. ASPH.
6-in. LIME-FLY ASH-AGGREGATE
12-in. ASPH

	PORTLAND CEMENT CONCRETE			ASPHALT CONCRETE		
ACTUAL OR POTENTIAL FLY ASH UTILIZATION	-	12 wt % IN BASE COURSE	12 lb/BAG OF PORTLAND CEMENT	4 wt % IN WEAR COURSE	4 wt % IN WEAR COURSE 12 wt % IN BASE COURSE	4 wt %
FLY ASH, lb/yd^3	-	480	65	160	640	160
lb/yd^2		53	18	13	93	53

NOTE SECTIONS SHOWN ARE TYPICAL AND ARE NOT INTENDED TO REPRESENT COMPARABLE DESIGNS

Fig. 4-12. Typical Highway Construction


AIRPORT
G & W H CORSON COMPARATIVE DESIGNS
NEWARK, END OF RUNWAY
4-in. ASPH
30-in. LIME-CEMENT-FLY ASH-AGGREGATE
NEWARK, CENTER OF RUNWAY
4-in. ASPH
22-in. LIME-CEMENT-FLY ASH-AGGREGATE
NEWARK, TAXIWAY
4-in. ASPH
28-in. LIME-CEMENT-FLY ASH-AGGREGATE
LONDON
16-in. CONT REINFORCED CONCRETE
8-in. LEAN CONCRETE
16-in. SUB-BASE
14-in. CONT. REINFORCED CONCRETE
8-in. ASPH BASE
6-in. SUB-BASE
4-in. ASPH
16-in. LIME-FLY ASH-AGGREGATE
16-in. LIME-FLY ASH-AGGREGATE
8-in. CONT REINFORCED CONCRETE
9-in. LIME-FLY ASH-AGGREGATE
9-in. LIME-FLY ASH-AGGREGATE

	NEWARK, END OF RUNWAY	NEWARK, CENTER OF RUNWAY	NEWARK, TAXIWAY	LONDON			
FLY ASH, lb/yd^2	405	297	378	NONE	NONE	432	244
PAVING COST, ESTIMATED $/yd^2	12.30	-	-	24.80	18.40	12.80	13.80
PAVING COST, REPORTED ACTUAL, $/yd^2	7.60	-	-	36.00	18.40	-	-

NOTE (1) DATA FROM a DESIGN PROCEDURE FOR AIRPORT PAVING SYSTEMS, POZ-O-PAC INTERNATIONAL, AUGUST 1970, AND
b NEWARK AIRPORT REDEVELOPMENT THE PAVEMENT STORY, THE PORT OF NEW YORK AUTHORITY, MAY 1969.

(2) FLY ASH PROVIDED FREE, WITH A TRANSPORTATION COST OF $2.50 - $3.00 PER TON

Fig. 4-13. Fly Ash in Airport Construction

Information and advice were provided and guidance for further inquiries was offered.

Inquiries were then made to the highway departments of 30 states to determine the following:

1. How and to what extent is fly ash employed?
2. Why is fly ash not used more extensively in existing applications?
3. Do existing specifications impose a significant inhibitory effect on the use of fly ash?
4. What recent fly ash tonnage has been utilized?

Twenty-five responses were received; a summary of these and two others is given in Table 4-14. From this information it was determined that fly ash is used by the states in the following manner and number:

1. Wear Course
   - Alabama
   - West Virginia (R&D)
2. Base Course
   - Ohio
   - Illinois
   - Pennsylvania
   - West Virginia
   - Virginia (R&D)
   - Kentucky (R&D)
3. Bituminous Filler
   - Pennsylvania
   - New Jersey
   - Michigan
   - Texas
   - North Carolina
   - New York
   - Kansas
4. Shoulders or Soil Stabilization
   - Illinois
   - New Jersey

Most responses were nonspecific as to the extent of fly ash used or the reasons why it is not used more. For example, one state highway department answered:

> "...we are knowledgeable regarding the various possible uses of fly ash in highway construction and have access to several sources of quality fly ash, but for several valid reasons, do not currently provide for its use in any appreciable quantity."

Table 4-14. Fly Ash Utilization in State Highway Programs

State	Present Uses	Called out by Specification	Highway Department R&D	Stated Factors Inhibiting Use	
				Technical	Economic
Alabama	Concrete additive, required in structures in or near salt water and in concrete pavement; permitted in bridges	Yes	Yes	--	Handling complexity, contractor resistance
Colorado	None	No	Yes	--	Yes
Connecticut	None	Yes	Yes	Permitted only for non-load bearing structures	--
Florida	None	No	Yes	--	Shipping cost; no local sources
Georgia	Concrete additive, though now largely discontinued	--	Yes	Low early strength	Local filler materials cheaper
Illinois	Shoulders, base courses; 7455 tons fly ash in CY 69	Yes	Yes	--	--
Iowa	Experimental base courses	No	Yes	Local fly ash contains excessive carbon	Shipping cost
Kansas	Bituminous filler	Yes	--	--	Contractor resistance
Kentucky	Experimental lime-fly ash-aggregate base courses	--	Yes	--	--
Maryland	None	No	Yes	--	Yes
Michigan	Bituminous filler; unsuccessfully in lime-fly ash-aggregate base courses	Yes	Yes	Base course frost-susceptible	Base course treatment more expensive than conventional; royalty requirement.
Minnesota	Very limited	No	Yes	--	--
Missouri	None	No	Yes	--	--
New Jersey	Filler bituminous concrete; soil stabilization	Yes	--	--	--
New Mexico	None	No	--	Specify 6-sack Portland cement concrete mix	--
New York	Bituminous filler	Modified C-618	Yes	--	--
North Carolina	Bituminous filler	No	Yes	Performance generally unsatisfactory in base course and pipe and block applications; variable color objectionable.	--
North Dakota	Bituminous filler	Yes	--	Lignite ash; Non-uniform quality	--
Ohio	Fly ash-lime-aggregate base	Yes	--	--	Contractor resistance
Pennsylvania	Extensive use as concrete additive, base courses, bituminous filler	Yes	--	--	--
Rhode Island	None	No	--	--	--
South Carolina	None	--	--	--	--
Texas	Bituminous filler; one project, 208 tons fly ash	Yes	Yes	--	Lack of supply (implied)
Virginia	Experimental lime-fly ash-aggregate base courses	--	Yes	--	--
West Virginia	Bituminous filler, lime-fly ash-aggregate base courses	Yes	Yes	--	--
Wisconsin	None	No	--	--	--
Wyoming	None	No	Yes	PCA Bulletin requires low early strength and wet curing	Shipping cost

Only Alabama cited the regular and obligatory use of fly ash as a batch constituent in portland cement concrete roadways. Also, its use in bridges is optional. Alabama presents a special case on several counts. First, their local aggregate is known to enter into reaction with the alkalies contained in cement; fly ash has been shown to retard these reactions. Second, fly ash is available from various power plants within the state. Third, in much of southern Alabama and, particularly, in the Mobile Bay area, their structures are exposed to brackish, sulfate-containing waters to which fly ash imparts a resistance in concrete. Nonetheless, their use of fly ash is rather nominal (12 to 18 pounds per bag of cement), and they have no plans to increase consumption for other reasons.

A few states reported that in some cases they employed lime-fly ash-aggregate base courses (pozzolan base), and a number have used nominal amounts of fly ash as a filler in bituminous pavements. And most states indicated that research and development programs on fly ash had been or are being pursued. A few stated that fly ash had been used one way or another, but that its use was discontinued because of the substandard performance of the structure. Very little tonnage data were provided.

A number of states voiced technical objections to the use of available fly ash, chiefly to its nonuniformity and nonreproducibility. These objections were for fly ash collected from many different power plants including load-following plants. Others objected to the relatively slow strength development of fly ash concrete for use as a wear course. They believe this could impede the progress of slip-form pavers, as well as prolong the interval before highway equipment can use the new structures. The low-early-strength inhibition is not valid since the application of the proper technology can negate it. Other states cited poor performance of fly ash-containing structures. It is probable, however, that imperfect technology has resulted in imperfect performance. For example, one state reported frost-heaving in lime-fly ash-aggregate base courses, while a contiguous state reported good success in the use of the same materials system. Inadequate subgrade drainage or poor batching and laying techniques could explain the apparent discrepancy in performance.

Despite these objections, little comment on the influence of specifications was offered. State specifications on fly ash are few in number, and where they exist seem to follow ASTM specifications closely.

Several states cited economic factors as inhibiting the use of fly ash, but frequently they were not specific. Shipping cost is an obvious factor; a readily available supply of acceptable local materials is another. A significant and generally justifiable economic objection is the resistance by the paving contractors to the use of a new product such as fly ash concrete for wear courses. The contractors have to post performance bonds and to warrant their work, and are reluctant to attempt to sell and place a product with which they are not intimately familiar. Besides, to produce fly ash concrete, for example, a contractor is required to buy, store, inventory, and transport an additional ingredient which is difficult to handle; to provide additional conveying equipment; and to run additional risks of mistakes in batching. His batching proportions are apt to be very different from those employed in regular concrete preparation, and crews must be sold on and educated to use new procedures.

Some potential users have objected to paying royalties on a patented lime-fly ash-aggregate base course such as Poz-O-Pac; no factual economic data which would bar fly ash from competing with other materials of equal quality on this basis were located. Others who pay royalties are perfectly satisfied and have expressed an appreciation of the research and assistance supplied by the parent company.

For urban paving, the price of pozzolan base course materials can be twice that of, say, conventional crushed stone base courses on a dollar per inch basis; however, only half the rock thickness is required for the pozzolan base. Moreover, numerous studies have shown that the deflection dish under a moving load on a pavement laid on a pozzolan base course is much more favorable for long life than the deflection of a similar pavement laid on a crushed stone base course twice as thick as the pozzolan course. Typical deflection patterns for pozzolan and crushed stone base courses are shown in Fig. 4-14 (Ref. C-108).

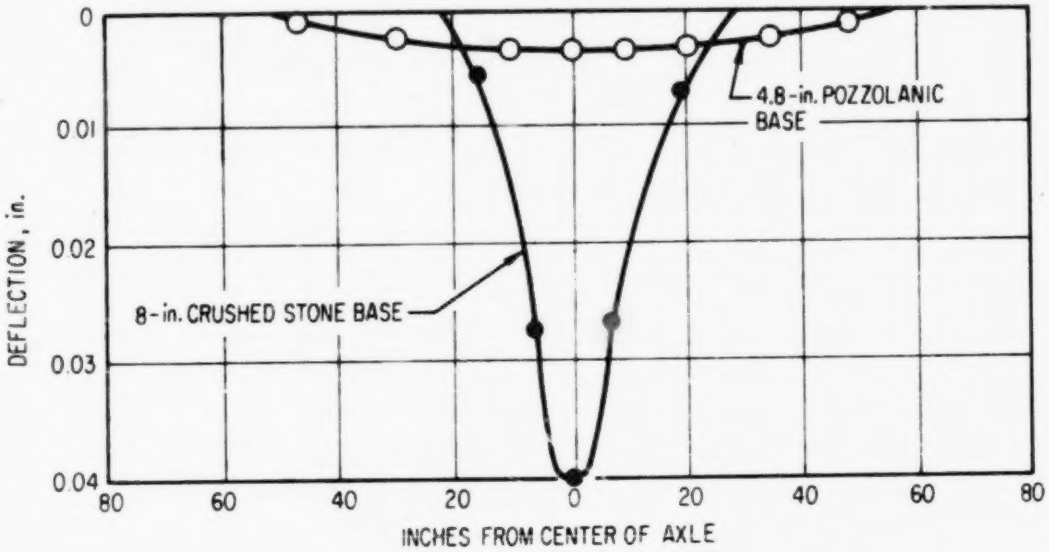


Fig. 4-14. Typical Base Deflection Pattern Under a Moving Load

According to one source[*], many cities permit the use of lime-fly ash-aggregate base course in their local projects. However, little fly ash is used. Certain municipalities tend to cheapen their construction through the use of inadequate thicknesses of crushed stone base courses. The predictable result is premature distress in the wear course, and frequent maintenance. From an initial cost standpoint, pozzolan base courses cannot compete with that form of construction as long as city governments are content with it.

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[*] Personal communication, 1971

When a semirigid base course is required for urban use, lime-fly ash-aggregate base course is a close technical and economic competitor for bituminous base courses and lean portland cement concrete base courses. The pozzolan base generally contains from 10 to 14 percent fly ash. For a given thickness, these materials have approximately equal strength qualities and, generally, the cost of a pozzolan base is less than that of a lean concrete or bituminous base within about 50 miles of the pozzolan base source. The pozzolan, however, offers a water tight base that is not prone to cracking or forming voids, is self-healing and continues to strengthen with age, and is not subject to freeze-thaw cracking. Superiority is claimed over the other two in that the lean portland cement concrete base is not water tight, does not have good resistance to freeze-thaw cracking, and cannot be driven on immediately after laying; neither the lean concrete nor the bituminous bases are self-healing, and structurally degrade with time.

Nevertheless, it is not unusual for a state to specify base course materials without including pozzolan base as an alternate in highway contracts, whether or not that state has a specification for pozzolan bases.

Certain observations on the presently limited use of fly ash road materials by the states can be drawn from information other than that supplied by highway department engineers. For example, some users and purveyors do believe that the fly ash concrete and base course materials discussed provide a valuable new, superior material of construction. They have developed the technology successfully, but the economic aspects are sometimes marginal. One reason is that a high-volume, low-value bulk material like fly ash can be shipped only so far. Because of this, plants that mix lime-fly ash-aggregate base course compositions are generally located close to the power plants, and can ship their products only 40 miles or so on a competitive basis. Yet, in some states it is estimated that 50 percent of the road construction is rural. Nevertheless, even though much of this fraction is out of economic shipping radius, a vast amount of paving is within reach of potential pozzolan base course supplies. In addition, portable mixing plants are finding some use; however, neither the technology nor the use is widespread.

These new technologies seem to have had little, if any, effect on most highway engineers who seem content with safe, well-developed technology. Technical risk and controversies are assiduously avoided. In some instances, highway departments successfully provided that improved and economic products be employed in their state highway programs. These instances were the results of persuasive campaigns by senior highway engineers appreciative of superior, economic engineering materials. Assistance was provided by individuals involved in fly ash research and sales.

Because of the difficulty of convincing state highway departments, some purveyors of fly ash seem to think that opposing the obstacles involved is not worth the effort. Additionally, overcoming the obstacles set by hostile trade associations, various competing lobbies, and other special interest groups is a formidable problem. This difficulty is not helped by the fact that there is no single jurisdiction by which one may operate with highway personnel. The American Association of State Highway Officials is an advisory body much like ASTM, and provides no direct jurisdiction. Several federal agencies such as the Highway Research Board, the Federal Highway Administration[*], and the Federal Aviation Agency are aware of fly ash and its potential uses, but these three agencies do not write specifications. It should be stressed that in the cases of the Federal Highway Administration and the FAA, their approval of local specifications is required in order that federal funds be allocated for highway and airport construction.

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[*] Formerly the Bureau of Public Roads

4.5.3 Fly Ash in Airport Construction

A brief survey of fly ash use in airport construction was made. The situation of airports is not particularly different from that of highways: the materials of construction are the same and both are constructed with public funds. An important precedent for the use of fly ash in airport construction was established recently (Refs. C-124 and A-4). The Port of New York authority elected to use lime-cement-fly ash-aggregate base courses in the redevelopment of the Newark airport. The only cost to Newark for the fly ash was $2.50 to $3 per ton, for transportation. The cost of laying the pozzolan base is $7 to $7.50 per square yard compared to about $12 for an equivalent conventional asphaltic concrete and up to $20 for a portland cement concrete pavement capable of sustaining equivalent loads. This superiority in economics is due in part to the low delivered cost of the fly ash and the use of in situ sand at the airport. Even under less favorable conditions, the pozzolan base would still maintain an economic advantage.

Although it is too early yet to assess the quality of this construction, preliminary indications seem favorable (Ref. C-124). Whether this precedent will provide an impetus to similar constructions seems to depend largely on local conditions and local agency attitudes.

4.5.4 Unique Foreign Applications

Three unique applications of fly ash road technology, two in England and one in Germany, are worthy of note since they are being used successfully and they offer additional outlets for fly ash in the United States.

In England, 2-1/2 million tons of fly ash will be used for highway structural fill in 1971. An example of this is a portion of the Birmingham to Exeter Motorway M5 (an expressway type road having 36-ft pavements on each side of a 13-ft median, and 9-1/2 ft hard shoulders). Fly ash is being used because of stability problems with alluvial soils (the alluvium being up to 90 ft deep in some places) and the height of the fill (26 ft). Other structural fill materials such as rock and soil cannot match those properties of fly ash that enable it to provide a stable road base. In fact, rock fills at depths greater than about 17 ft would: (a) overcome the compressible base, and (b) require greater land acquisition because the side slopes cannot be as steep as with fly ash. Lower bulk density, superior compaction and some pozzolanic reaction are distinct advantages of fly ash.

The fly ash is transported mostly by rail for this project, in a moist condition with the water content 40 percent maximum. The water simplifies hauling and is necessary for compaction. A layer of crushed rock is spread over the alluvial soil to allow water to move through the base, and a layer of fine rock is spread over that to prevent choking by the fly ash. On this, 100 percent fly ash that has been moistened is laid in 9-in. thicknesses (lifts), and compacted. This procedure is continued until the equivalent of 30 ft is laid. Compaction of the 9-in. lifts produces a 26-ft embankment (a total compaction of 4 ft). This will remain for a year, settling at a rate of about 4 in. in 15 ft. That will be topped off with a 6-in. sub-base of crushed rock, then 8 in. of dense asphalt put in three lifts of 3, 3 and 2 in. Then it is surfaced with 4 in. of hot rolled asphalt put in two lifts of 2-1/2 and 1-1/2 in. containing coarse aggregate for skid resistance.

After the fly ash embankment is compacted, it is seeded with grass by a system called hydro-seeding in which a mixture of seed and liquid fertilizer is hosed onto the embankment. Hydro-seeding is applied only once. After that, the grass is cut but not raked so that it will supply its own organic nutrient thereafter. The small amount of boron in the fly ash is poisonous to people and animals; therefore, it is fenced off. Clover, which absorbs boron is included in the seeding. At the end of a growing season, the grass is burned off and allowed to grow back. After two years, the boron is reduced to a negligible amount.

A further use indicated in England is a parking lot and secondary road base course material consisting of 88 to 90 percent fly ash plus cement and water. This material is generally used in 6- or 7-in. thicknesses, providing a compressive strength of 400- to 500-psi. Data to verify the adequacy of this material have not been obtained.

In Germany, a unique method of paving, called "Gans Paving" is used for secondary roads and for expressway ramps. This type of paving uses a slurry consisting of 10- to 12-percent asphalt with aggregate up to 1-1/2 in., and 28 percent fly ash. Although used for secondary roads only, this system incorporates considerably more fly ash than normally allowed (about 4 percent) as a filler in bituminous paving in the United States.

4.5.5 Potential Utilization

The use of fly ash in road building has a very high potential; however, this use from a national standpoint is not encouraging based on present circumstances. Although its value in structural concrete and as base courses and structural fill is understood, government agencies that originate roadway contracts are not, on the whole, specifying fly ash. The risks and problems of supply, quality and handling involved for concrete wear course materials are a strong inhibitor for that usage. Road building is seasonal, and demands large volumes of high quality fly ash for wear courses in a short period of time, creating storage and stockpiling difficulties for which utilities are not normally prepared. Little hope can be expressed for fly ash in wear courses; however, fly ash can be openly stored in the winter, and with minimal processing, be used as an ingredient for base course materials during the construction period which may last from about 6 to 8 months, with some exceptions. This available, economical supply (the quality does not have to be high), plus the normal supply, coupled with the many advantages of pozzolan base courses, should make this a large outlet for fly ash. If this is to be the case on a large scale, however, it may take government encouragement to break through the resistance of highway departments and contractors to make a change from well-established habits and methods.

The use of fly ash as a structural fill material for roads produces excellent results, but it is a rare case when fly ash can compete with rock and soil for the same purpose. Except for isolated cases where large sums would be used, this use is considered small on a continuing national scale.

Fly ash as a mineral filler is a proven utilization employed in several states. Its use in small percentages of thin layers of pavement, plus competition from inexpensive materials, prevent this from becoming a large consumer of fly ash.

4.6 DEVELOPMENT PROGRAMS

It is difficult to state with certainty that technically feasible uses of fly ash exist but have not yet been identified. There is presently a considerable effort in determining new uses for fly ash, but a considerable amount of work remains to be done both in research and development. The fundamental research that provides the intrinsic characteristics and properties of this material should rank among the highest priorities of tasks to be accomplished. Much of the time and money being spent on product development might have been obviated had an understanding of the behavior of fly ash pre-existed. The establishment of a sound technical base would provide the foundation for future product development and expedite the growth of the fly ash industry. Even though the fly ash industry has expanded many fold through the last ten years, the research on which new technology can be based is being conducted by an extremely small group of individuals.

Fly ash as a raw material has the potential for many undeveloped uses. Examples of these uses must include the work conducted at the University of Notre Dame on the utilization of regular fly ash in the treatment of polluted waters. The potential for this use was demonstrated and should be investigated further, especially in view of its synergistic relationship. The suggestion that limestone-modified fly ash may be even more effective in treatment of polluted waters should be investigated.

A grossly neglected area of research is in the production of ceramic products. The development of bricks from fly ash has demonstrated the capability of material substitution in this product. The research to determine whether fly ash could be a material substitute in other uses of ceramic raw materials such as glasses, glazes, tile, whiteware, clay pipe and others has not been conducted. The similarity in the chemical content of fly ash and that of the raw materials for most of these products is obvious. Yet, the only work directed toward this potentially huge market has been done on a very limited effort by Rutgers University (Ref. C-50). Their recent work on glass and

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glass/ceramics has extremely high potential value, but the size of this effort is inadequate for the research required in this area.

The role that fundamental research may play in developing a market for fly ash is given by the following example. Although fundamental research was not involved, it was, however, the understanding of physical characterization that led to the recovery of the microscopic glass bubbles that rise to the surface of disposal lagoons (Ref. C-112). These hollow glass spheres, called cenospheres, are finding many uses as a lightweight filler components in specialty construction applications such as deep-diving submersible vehicles.

An obvious use of fly ash for which there is no known work being conducted in the United States is the development of gas concrete for the manufacture of building materials. This use of fly ash is being successfully employed in numerous foreign countries (see Section 4.2.8). In view of the possible structural variability and the existence of a potentially superb market in this country, this application of fly ash deserves considerably more attention than it has received.

There are numerous other research and development projects that have been undertaken to utilize fly ash. An annotated list of references of such work has recently been compiled by Cockrell, Shafer, and Leonard and lists the following topic areas: adsorptive material, brick manufacture, building materials, coagulant, metal and mineral ore recovery and miscellaneous uses. A total of 146 such references is listed in Ref. B-4.

4.7 FLY ASH USE-INHIBITIONS SUMMARY

The inhibitions to the use of regular fly ash are covered in the discussions of each potential utilization category within Section 4. Many of those inhibitions are applicable to numerous utilization schemes and would undoubtedly have an impact on the development of new uses. The following listing of inhibitions provides an overview of the total situation related to the problem of why the utilization of fly ash is severely limited:

1. Lack of understanding or appreciation of the applicable technologies by the general public (i.e., concrete, road base courses)
2. Lack of improvement of existing technologies or development of new ones (i.e., structural concrete, lightweight aggregate, gas concrete, ceramics, mineral recovery, etc.)
3. Irrelevance of existing specifications for fly ash as an admixture in portland cement concrete
4. Lack of initiative on the part of power companies to treat the production of fly ash as a profitable business, resulting in the non-production or inconsistent production of good quality fly ash to be marketed directly by the power companies or offered for sale to fly ash brokers
5. Lack of sufficient adequate sales organizations to act as a catalyst between power companies and fly ash users (i.e., power companies not sure of market, users not sure of supply)
6. Reluctance of individuals to change (i.e., concrete, road base courses)
7. Inability to economically compete with other materials for wide scale usage (i.e., cement manufacture, structural fill, bituminous filler, bricks)
8. Geographic limitations imposed by hauling costs (i.e., small supply in Western United States; too few Eastern United States power companies producing, collecting, storing usable fly ash)
9. Difficulty in handling and transporting; additional equipment and operational procedures required
10. Spread of misleading information (i.e., bad color, inadequate early strength, waste material); and adverse publicity resulting from improper usage

SECTION 5

WET-LIMESTONE-MODIFIED FLY ASH SURVEY

5.1 SCOPE OF SURVEY

This portion of the program consisted primarily of surveys of efforts being made to determine potential uses for wet process limestone-modified fly ash, and the determinations of efforts necessary to cause the utilization of this material. Technically and economically feasible products utilizing modified ash have not been determined. When they are, it is expected that the marketing processes of the ash will be similar to those now used or projected for the regular (unmodified) ash. Therefore, the major effort of this total study, which relates to the utilization of regular ash, will be applicable to the modified ash in many respects.

A brief review of research directed by EPA for the determination of potential uses for limestone-modified fly ash is given in the following paragraph. That work was performed at the Coal Research Bureau, West Virginia University.

5.1.1 Limestone-Modified Fly Ash Research Performed at the Coal Research Bureau

5.1.1.1 Dry-Collected Limestone-Modified Fly Ash

The objectives of this effort was to characterize the dry-collected limestone-modified fly ash using mineral dressing techniques and to evaluate the feasibility of utilizing the dry-collected limestone-modified fly ash to manufacture saleable products. Among the products investigated were: mineral wool, concrete, soil amendment, and mineral recovery. This effort resulted in the classification of a number of possible uses for the material into technically potential categories as follows:

a. Low Potential
   1. mineral recovery
   2. fluxing agent
   3. lightweight aggregate
   4. fired structural products
   5. unreacted calcium recovery

b. Medium Potential
   1. acid mine drainage neutralization
   2. concrete admixture
   3. cement kiln raw material
   4. soil stabilizer and amendment

c. High Potential
   1. mineral wool
   2. sulfur recovery

5.1.1.2 Wet-Collected Limestone-Modified Fly Ash

The objectives of this effort are to characterize the gross chemical and physical properties of wet-collected limestone-modified fly ash in order to get a preliminary indication as to the possibility of substituting the modified ash for regular fly ash in some of the more prominent fly ash utilization schemes as well as in a limited number of new applications. Included in the list of applications to be investigated are: production of SO_2, soil amendment, brick manufacture, producing heat treated materials, recovery of minerals, and manufacture of structural materials. For the processes that have been investigated to date, their technical potential has been broken down in two categories.

a. Low Potential
   1. flotation as a means of recovering separate fractions

b. Good Technical Potential

    1. sulfur recovery
    2. sand-lime brick
    3. mineral wool

This work, which was begun recently, is continuing in the following areas:

a. Soil amendment
b. Basic chemical and physical characterization of slurry and sludge
c. Ceramic materials
d. Recovery of SO_2 (thermal)
e. Calcium-silicate brick
f. Flotation
g. Dewatering
    1. settling
    2. flocculants
    3. filtration
    4. centrifugation
h. Gas concrete
i. High pressure alumina leaching

5.2 MODIFIED ASH PRODUCTION AND CONSIDERATIONS

The wet collection (adsorption) system is undergoing developments in numerous localities in the United States. Units are in various phases of installation, development, or operation in Kansas, Missouri, and Kentucky, plus the installation of experimentation units at the TVA Shawnee plant near Paducah, Kentucky. Additionally, similar units have been installed in several foreign countries. At this time, none of these is operating continuously at rated efficiencies; however, corrections are being made and improvements are being achieved.

The problems that face the utilization of the modified ash are centered in several areas: (a) the quality of the ash is affected appreciably by the sulfur content of the coal burned, and by the efficiency of the combustion and scrubbing process (see Table 5-1); (b) the ash is generally slurried to a pond where the residue (sludge), being a pozzolan in the presence of lime and water, is subject to "concreting;" (c) the sludge contains sulfur which creates additional problems of sulfur gas collection for many manufacturing processes employing high temperatures; (d) the pozzolanic properties of the ash are decreased; (e) if wet scrubbing is preceded by limestone injection into the furnace, the volume of ash produced will generally be between 1.5 and 3 times as much as without the modified process; and (f) water in the settling pond is generally not conducive to the good health of fish or humans. On the plus side, the modified ash contains: (a) possibly pozzolanic properties, (b) nominal amounts of unreacted lime, and (c) appreciable amounts of gypsum.

Research has shown that potential uses for the modified ash may exist, but the technical and economic feasibility will have to be determined through research and development programs.

5.3 SURVEY OF WET PROCESS SYSTEMS

Although the study of the mechanics of SO_2 removal systems was not an element of this program, utilities in Kansas City and Lawrence, Kansas, and St. Louis, Missouri, which have installed wet scrubber systems were visited because (1) the combustion and collection processes appreciably affect the quality and quantity of the modified fly ash, and (2) regular ash is being marketed in some of those areas. Two of the three utilities visited were engaged in the selling of fly ash (the third had burned coal infrequently and did not have an ash collection system). Each of the two that do collect fly ash, sell up to approximately 100,000 tons of fly ash per year. One had investigated the possibilities of utilizing the modified ash and had determined for his market area: (1) that the sulfur market was practically saturated and therefore there was no interest in sulfur recovery; and (2) there

Table 5-1. Wet-Adsorbed Limestone-modified Fly Ash -* Theoretical Variations in Chemical and Phase Composition with Variations in Sulfur and Ash Content of Coal Burned

		10% Ash in Coal		20% Ash in Coal	
Composition (Weight Percent)	Typical Fly Ash (Unmodified)	Sulfur Content of Coal			
		1%	4%	1%	4%
SiO_2	45	30.6	16.2	36.8	23.9
Al_2O_3	23	15.7	8.3	18.8	12.2
Fe_2O_3	19	12.9	6.8	15.5	10.1
TiO_2	1	0.7	0.4	0.8	0.5
CaO	2	14.4	28.5	9.5	21.5
MgO	1	0.7	0.4	0.8	0.5
SO_3	0.7	17.5	36.2	10.8	26.9
Alkalis	2.3	1.6	0.8	1.9	1.2
LOI	6	4.1	2.2	4.9	3.2
Relative Ash Quantity	1.00	1.47	2.77	1.22	1.88
Gypsum	0	28.3	60.1	17.5	43.5
Free Lime	2.0	2.8	4.5	2.3	3.7
Fly Ash	97.3	66.3	35.1	79.5	51.6

Notes:

*Wet adsorption preceded by dry injection of limestone into furnace. Only ash collection device is wet scrubber.

1. Values given for gypsum include both sulfates and sulfites, but exclude combined water.
2. Sulfur collection system assumed 95 percent efficient.
3. Limestone added at 110 percent stoichiometric. Limestone assumed to be 100 percent $CaCO_3$.

is little hope for selling fly ash mineral wool in competition with glass wool. The other believes there is a very low potential for the utilization of the modified ash and that it would eliminate his present fly ash market. It appears certain that the modified ash is not going to be widely utilized without the aid of further research.

The fact that coal containing varying degrees of sulfur, whether washed or otherwise preconditioned (see Section 5.4), presents a vague picture as to the amount and quality of modified fly ash that will be produced. This indicates that research performed for the determination of uses for the modified ash must consider the wide variations that may exist in the chemical and physical qualities of the ash.

5.4 WET PROCESS LIMESTONE-MODIFIED FLY ASH PROPERTIES AND QUANTITIES

A theoretical chemical analysis of the modified ash reveals the wide range of values attached to the chemical constituents depending on the sulfur content of the coal and the percent of coal burned which becomes fly ash. Physical phases vary widely in the same manner. An example of this is given in Table 5-1. Values are shown for 10 and 20 percent fly ash content coal and for a sulfur content of 1 and 4 percent in each case. Although the production of ash at 20 percent of coal burned is higher than present data would indicate, that column in the table provides other data points which indicate trends. Not only are the variations in properties great, the differences when compared to the unmodified ash are considerable, and the modified ash is wet-collected. In addition, the amount of modified ash produced per pound of coal burned may be as much as nearly three times the amount produced without limestone injection.

It is significant that certain actions or considerations are necessary if the modified ash is to be used:

a. Research into the characterization of the ash, and its utilization, must consider the wide variations in material properties. For widespread utilization, efforts should be expended to: (1) determine uses which are not particularly sensitive to material properties variations, and (2) determine uses based on particular materials properties in the event that variations are minimized by way of specialized coal procurement, coal treatment, closely supervised and maintained combustion and collection equipment, or beneficiation of the ash.

b. The stabilization of the quality of the modified ash at a given utility, if necessary for utilization, is largely dependent upon the utility's concern for and ability to do so.

c. Most products made from the modified ash are not expected to economically compete with the same products made from unmodified ash. Since many utilities will not necessarily convert to a limestone-injection wet-scrubbed system, or will have provisions to collect the ash dry or unmodified prior to gas scrubbing, development programs for modified ash products should include considerations of the effect of competition with similar utilizations for unmodified ash. Additionally, developments for modified ash should include considerations for new applications which are favorable to the use of this material over unmodified fly ash.

d. A further consideration of the limestone-modified fly ash situation is a potential toxicity problem. Several analyses of dry collected limestone-modified fly ash have been performed by the Shell Development Co. and Oak Ridge Laboratories to determine trace metal constituents in the ash (see Appendix G). These analyses are incomplete preliminary data and, although they were performed on dry collected modified ash, they indicate that appreciable amounts of toxic materials would also exist in the wet-collected modified ash. If toxic materials in the ash exist in soluble form, the leachability to ground water supplies from mine fills, land fills, and road bases, would have to be considered. There is the potential problem that bacteria could attack the material giving off undesirable H_2S gas. Furthermore, to prevent harm to fish life in streams due to overflow or seepage from ash ponds, it may be necessary to aerate the pond waters to convert sulfites to sulfates to prevent deoxidation of the stream water.

5.5 WET-SCRUBBED LIMESTONE-MODIFIED ASH RESEARCH

Research programs and investigations of a rather limited nature are proceeding at various locations. Probably the most comprehensive is the research being performed at West Virginia University's Coal Research Bureau and at the Combustion Engineering Company. Others are at Michigan Institute of Technology, G. and W. H. Corson Company, and several engineering companies in the Philadelphia and Pittsburgh, Pennsylvania areas. Uses being studied or considered include those for which the unmodified ash is being or could be used, plus new developments. The following list provides an overview of those considerations, and includes uses that may be possible regardless of how slight their potential is.

a. Uses Same as or Similar to Those for Actual or Potential Unmodified Fly Ash Uses

1. Concrete Admixture (Structure and Products)
2. Manufacture of Portland Cement
3. Fired Brick
4. Filler in Bituminous Concrete
5. Lightweight Aggregate
6. Road Base Course
7. Structural Fill
8. Soil Amendment
9. Mine Void Fill
10. Sewage Plant Treatment
11. Mineral Wool*
12. Neutralization of Acid Mine Drainage and Polluted Waters
13. Mineral Recovery

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*Technology for this use, employing dry-collected modified ash, has been developed at West Virginia University. Inhibitions, if they exist, are in the comparative economics of manufacture and in the likelihood of overcapacity in competition with mineral wool and fiberglass insulation materials. To date, a market position for fly ash mineral wool has not been found.

b. Potential New Uses

1. Asphalt Additive - sealant for lake and reservoir linings, roofing
2. Waste Disposal/Sanitary Structural Land Fill
3. Autoclaved Products - gas concrete, bricks, mineral aggregate
4. Hot Press Sintering - pipes, metal coatings
5. Wallboard, Plaster
6. Product Recovery - sulfur, lime, regular fly ash
7. Sulfuric Acid

There may be other uses or processes of a proprietary nature which have not been identified.

5.6 BASIC QUALITIES OF THE MODIFIED ASH AFFECTING UTILIZATION

The qualities of wet collected limestone-modified fly ash when compared to those of unmodified ash are in general inferior when considering most known uses for fly ash. On the other hand, the modified ash apparently has potential applications for several of the current uses for fly ash in addition to some new uses. The most significant qualities or conditions affecting its potential utilization are:

a. It is produced in a wet state and will have to be dewatered for many uses to prevent agglomeration due to the interaction of the pozzolan with self-contained lime in the presence of water.
    1. Dewatering may alter the properties of the ash.
    2. Agglomeration can require a grinding operation depending on fineness required.

b. Its use in the manufacture of sintered products has three distinct disadvantages:
    1. Sulfur is released and would have to be collected.
    2. Decomposition of sulfates (or sulfites) takes place at temperatures below sintering and results in the physical destruction of the "green formed" product.

3. The fusion temperature is lowered such that a short range exists between sintering and melting, thereby requiring a sophisticated temperature control system for the sintering process.

c. Its pozzolanic properties are reduced because the sum of the SiO_2, Al_2O_3, and Fe_2O_3 content and consequently the glassy phase is reduced (see Table 5-1). This may be somewhat mitigated by the content of more unreacted lime, particularly in uses where lime is normally added to the product mix.

d. Sulfates may exaggerate set retardation in cementitious products, and leaching may cause subsequent properties degradation.

e. Ash properties can be highly variable (see Section 5.4). Blending may be required for many applications.

f. An adequate characterization of the wet-collected modified ash has not yet been performed.

g. Wet-collected modified fly ash should be amenable to autoclave processes, but verification of this potential has not been demonstrated.

h. It should be amenable to several ambient condition or low temperature processes.

i. The presence of gypsum (often as a major component) offers the potential for new uses.

j. The presence of sulfur, calcium, aluminum, iron, and other constituents offers the potential for mineral extraction.

k. There are the obvious economic problems of handling and transporting the modified ash, either wet or dry.

Although this list of qualities of wet-collected modified fly ash is not necessarily complete, it does represent the expected behavior as interpreted from the small amount of data and information that currently exists. Until appropriate applications are explicitly defined, the various advantages or disadvantages of modified ash cannot be accurately assessed.

5.7 EVALUATION OF UTILIZATION WITH SIGNIFICANT USE PARAMETERS

An assessment of potential uses of wet-collected limestone-modified fly ash against the significant qualities or conditions associated with the ash was made. To determine the applications worthy of development, deletions and selections were made on the basis of the following factors in light of the qualities and conditions listed in Section 5.6:

a. Potential technical feasibility
b. Potential economic feasibility
c. Potential large tonnage usability

Therefore, the following uses were eliminated: concrete admixture, manufacture of portland cement, fired brick, lightweight aggregate, mineral wool, and soil amendment. As applicable, these deletions were based primarily on the economic disadvantages associated with dewatering, sulfur collection, low pozzolanic properties, and competition from less costly products. These disadvantages may not necessarily exist in every locality, but they are considered to be generally applicable. If there were a potential market for recovered sulfur, then the development of modified ash sintered products coupled with sulfur collection would be advisable. However, an analysis of the sulfur and sulfuric acid markets, combined with potential considerations of the unmodified ash sintered product markets should precede technical developments of that sort. This conclusion is based on the fact that opinions have been given that, in general, new sulfur supplies are not in great demand, and large scale marketing of unmodified ash sintered products has not been established.

The following listing separates potential uses into generic classes and provides comments on usability for each. The lack of specific technical and economic data and potential toxicity effects precludes definitive detail and therefore, best estimates are offered.

a. Filler Material

1. Structural fill, mine void fill, and land fill - Adequate for many applications. Effects of soft gypsum phase not understood. Toxicity of leaching to be studied.

2. Filler in bituminous concrete, asphalt additive, low-grade concreting of wastes (including food wastes) for sanitary structural land fill - Research and development required. No apparent difficulties.

b Pozzolanic Products

1. Road base course - Research and development required. Impact of soft gypsum phase not known. Apparent weakened pozzolan may restrict this use.

c. Autoclave Products

1. Mineral aggregate (Ref. Michigan Institute of Technology), gas concrete (Ref. 4.2.7), cast or formed shapes - Research and development is required. High potential both technically and economically.

d. Pressure Sintered Products

1. Most sintered products - Research and development required, questionable production economics.

e. Gypsum Products

1. Wallboard, wall plaster - Research and development required. Appropriate use for many high sulfur ashes.

f. Mineral Recovery

1. Lime, aluminum, iron, pozzolan (glass particles), titanium, silicon, rare elements - Research and development required. Offers very high ultimate potential.

g. Sulfur Extraction

1. Sulfur and sulfuric acid (by-product) - Not directly economical, but may be a required by-product for other uses of the ash.

h. Polluted Water Treatment

1. Recovery of polluted streams, ponds, lakes - Research and development required. Soluble lime is effective in precipitating phosphates from polluted waters.

5.8 RESEARCH CONSIDERATIONS

The successful utilization of limestone-modified fly ash cannot be expected without adequate research and development. It is only from such programs that appropriate technology can evolve to provide the basis for economic utilization. Some of the considerations for proposed research are discussed in the following sections.

5.8.1 Characterization

The most critical research required for expedient development of utilization technology for limestone-modified fly ash is the characterization of the ash. Whereas the chemical analyses that have been used in the past serve a valuable purpose, they are not adequate for defining or evolving new technologies. Chemical and physical characterization of wet-collected fly ash must include phase analysis, elemental compositon (including trace elements), states of oxidation, physical state, size distribution of particles, and electrolyte levels. Techniques such as mineralogical and petrographic analyses, spectroscopy, scanning electron microscopy, electron probe microanalysis, and ion probe mass analysis are valuable tools for adequate characterization.

It is appropriate to reiterate the importance of adequate characterization of the ash for the effective conduction of subsequent utilization research efforts. The information gained from the analyses as suggested are critical to schemes by which the ash can be either beneficiated for some types of mass usage, or used as an ore material for mineral recovery.

5.8.2 Mass Usage of Limestone-Modified Fly Ash

Several potential mass uses of limestone-modified fly ash were suggested in Section 5.7, but most required some research and development and at least verification of its technical usability. Such verification is necessary for structural fill and filler materials for bituminous concrete. A minimal amount of research and development may be necessary for these uses, but competing low cost alternate materials (including regular fly ash) prevent extensive research or beneficiation as a means for promoting its use. Research in the area of road base course materials may depend heavily on progress already made in private industry.

Limestone-modified fly ash for most potential utilizations is a new material with unique characteristics. It cannot be thought of as just as modified fly ash, and therefore, an extension of existing fly ash technology to limestone-modified fly ash is not valid. Much of the research that has been conducted on regular fly ash for the purpose of specific applications should be repeated with the modified ash where utilization potential warrants investigation.

Other mass uses such as autoclave products, pressure sintered products, and gypsum products will each require extensive research and development and, in many cases, the fly ash may require beneficiation to be usable. Many of these applications may be competitive with alternative materials, even with beneficiation. Research to identify these applications and determine a suitable beneficiation scheme is required.

A particularly efficient system may be one of total utilization in which various products emerge from a single installation. For example, such a unit could produce mineral aggregate, lightweight aggregate, sulfur or sulfuric acid, recovered minerals, and filler for bituminous products. Any unused ash from this operation would either be available for land fill or be disposed of otherwise.

5.8.3 Toxicology

It has long been recognized that fly ash, and for that matter almost any earthy material, contains trace quantities of numerous heavy metals and other toxic elements. These usually are in solution in silicate glasses or immobilized as compounds or solid solutions, and thus are generally innocuous to flora and fauna.

The situation with limestone-modified fly ash may not be so innocuous. The process involves chemistry which is not yet perfectly understood. Moreover, in the wet scrubber variation, soluble compounds, sulfites, and sulfates are involved. Whether the dangerous species enter into these reactions has not, to our knowledge, been clarified. For example, barium, an alkaline earth whose chemistry is similar to that of calcium, could conceivably form $BaSO_3$; this compound has a measurable solubility in water at 20°C. Cadmium forms soluble sulfite and sulfate compounds; and $BeSO_4 \cdot 4H_2O$ is quite soluble. The chemistry of vanadium is somewhat more complex. Vanadyl sulfate is known, and is reported to be very soluble in water.

Recently received from EPA are spark source mass spectrographic analyses of several size fractions of a TVA dry-collected limestone-modified fly ash (see Appendix G). These were provided by the Process Measurement Section, Division of Control Systems, Office of Air Programs. It should be noted that these data resulted from a limited sampling only and that toxicology problems have not definitely been determined. Several interesting features were noted, however. The elements of concern showed little tendency to be concentrated in any size fraction, five of which ranged from average diameters of 28.7μ down to 1.5μ. In all size fractions, however, certain elements were reported at levels high enough to cause concern, e.g., As, 50 to 200 ppm; Ba, 200 ppm; Pb, 200 to 500 ppm; V, 200 ppm. These levels should be verified by several different analyses. Moreover, it should be ascertained whether the dangerous species originated in the limestone, the coal ash, or both. Any soluble constituents that can be leached from this ash deserve attention. Solvents of interest are fresh water, sea water, and saline solutions typical of body fluids. Further solvent variables might be temperature, pH, and oxidation or reduction potential. Any positive evidence of appreciable dissolution of toxic substances would then necessitate reappraisal of utilization or disposal schemes, particularly those in which the modified ash might be exposed to ground waters.

5.8.4 Mineral Recovery

The recovery of minerals from dry-collected limestone-modified fly ash has been examined in a comprehensive study by research scientists at the Coal Research Bureau, West Virginia University (Ref. D-39). From this work has developed a preliminary conceptual plan for an Emission Control Minerals Complex (ECMC) to utilize all parts of modified fly ash. The ECMC process involves slurrying modified fly ash with water followed by (a) carbonation of the slurry to convert unreacted lime and magnesia to their carbonate form, (b) concentration of the lime from the carbonated modified fly ash by agglomeration flotation for reinjection into the furnace, (c) melting of the concentration rejects for the manufacture of such products as mineral wool, and (d) recovery of the relatively clean and more concentrated sulfur gases evolved from the melt for the manufacture of such products as sulfuric acid.

The technical potential and feasibility of the ECMC has been demonstrated on a pilot plant scale. The economic viability of the process seems to remain in doubt.

Numerous techniques available to the extractive metallurgist and chemical engineer could prove appropriate for the extraction of minerals from modified (and unmodified) fly ash. Various aspects of hydrometallurgy could, for example, be employed in the extraction of mineral values. Electrolysis and electrophoresis, both aqueous and in a melt, may prove feasible for the destruction of fly ash and the separation of its constituents. Pyrometallurgical schemes may be employed for oxidation, reduction, and separation of mineral values. Numerous physical processes involving density, size, surface chemistry, and magnetic qualities could prove useful.

The application of any of these potentially useful processes requires -- first and foremost -- a sound and detailed knowledge of the qualities of the feed material (see Section 5.8.1). Without such knowledge, which must be gained in programs of detailed laboratory evaluation, rational programs of mineral recovery will be very difficult, if not impossible, to develop. Such evaluation studies should be initiated and taken to a fairly advanced state before serious attempts at mineral recovery are undertaken.

5.9 UTILIZATION INHIBITIONS

The inhibitions to the utilization of wet-scrubbed limestone-modified fly ash are centered around the fact that it is a new material which is not well understood, and for which applications have not been developed. It is not applicable as a direct substitute for regular fly ash because its chemical and physical properties are drastically different from the properties of regular ash. It does have a potential utilization for some existing applications of the regular fly ash, but developments are required. Also, its unique properties make it amenable to new uses for which the regular ash is not usable, or which have not been developed. In any event, programs of study, research and development are required before the modified ash can be utilized.

Detailed discussions of these inhibitions are given in Sections 5.6 and 5.7.

APPENDIX A

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APPENDIX A

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ABBREVIATIONS USED IN BIBLIOGRAPHY

Amer. Assn. of State Hwy. Off.	American Association of State Highway Officials, Washington, D.C.
A.C.I. Jour.	American Concrete Institute Journal
ASTM	American Society for Testing Materials, Philadelphia
Batt. Mem. Inst.	Battelle Memorial Institute, Columbus, Ohio
Bldg. Resch. Lab., O.S.U.	Building Research Laboratory, Ohio State University, Columbus, Ohio
Bu. M.I.C.	Bureau of Mines Information Circular
Chem. Eng.	Chemical Engineering
Civ. Eng.	Civil Engineering
C.R. B.S.M.	Coal Research Bureau, School of Mines, Morgantown, West Virginia
Edison Elec. Inst.	Edison Electrical Institute, New York, New York
Elec. World	Electronic World
Eng. N. Rec.	Engineering News Record
Env. Sc. & Tech.	Environmental Science and Technology
Hwy. Resch. Bd.	Highway Research Board, National Academy of Sciences, National Research Council, Washington, D.C.
Hwy. Resch. Rec.	Highway Research Record
K.B.P.	Ken Bar Paper (NAPCA, Division of Process Engineering, Dry Limestone Injection Process Symposium, Gilbertsville, Kentucky)

Mech. Eng.	Mechanical Engineering
Min. Eng.	Mining Engineering
NAPCA	National Air Pollution Control Administration, Washington, D.C. (now APCO)
N.A.A.	National Ash Association, Washington, D.C.
N.R.M.C.A.	National Ready Mixed Concrete Association, Silver Springs, Maryland
P.C.A.	Portland Cement Association, Skokie, Illinois
Pow. Eng.	Power Engineering
2nd A.U.S.	Second Ash Utilization Symposium, Pittsburgh, March 1970
Tech. Lab., C.R.I.E.P.I.	Technical Laboratory, Central Research Institute of Electric Power Industry, Tokyo, Japan
U.S.C.E-W.E.S.	U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi
U.S. Dept. of H.E.W.	U.S. Department of Health, Education and Welfare, Washington, D.C. (now EPA)
U.S. Dept. Int. I.C.	U.S. Department of the Interior Information Circular
U.S. Dept. Int. R.I.	U.S. Department of the Interior Report Investigations

APPENDIX B

ACKNOWLEDGEMENTS TO SOURCES OF FLY ASH DATA

This appendix acknowledges the data of great value to this study that were provided by individuals in industry, universities, trade associations, and government agencies.

B. 1 FLY ASH PRODUCTION, BENEFICIATION, AND MARKETING

Data Source	Primary Contact	Data
American Electric Power Service Corporation Charleston, W. Virginia	Ronald E. Morrison	Fly ash production, marketing
American Electric Power Service Company New York, New York	S. J. Marmaross	Fly ash production, marketing
Appalachian Power Company Charleston, W. Virginia	Henry Scaggs	Fly ash production, collection
Central Electricity Generating Board London ECI, England	Alex Wilson	Fly ash production, marketing
Chicago Fly Ash Company Chicago, Illinois	C. E. Lovewell E. Hyland	Marketing
Consolidated Edison Company of New York, Inc. New York, New York	William Bannon	Fly ash production
Dayton Fly Ash Company Pittsburgh, Pennsylvania	Lou Marcuz	Marketing
Dayton Fly Ash Company Smyrna, Georgia	Robert Styron	Marketing, beneficiation

Data Source	Primary Contact	Data
Duquesne Light & Power Pittsburgh, Pennsylvania	M. Jaworski Dan Joseph	Fly ash production, marketing
Edison Electric Institute New York, New York	G. A. Olson	Edison Electric Institute survey
Environmental Policy Division Legislative Reference Service Library of Congress Washington, D. C.	Harry Perry	Fly ash production
National Ash Association Washington, D. C.	John Faber Philip Meikle	Fly ash production, marketing
Southern Electric Generating Company Birmingham, Alabama	Charles Brackett	Fly ash production survey for 1970, general utilization
Southern Fly Ash Company Birmingham, Alabama	Mr. Hardison	Fly ash production, marketing
Steinkohlen Elektrizitat AG Essen, W. Germany	Hermann Erythropel	Fly ash production
Stirling Sintering Company South Heights, Pennsylvania	Harold T. Stirling Charles R. Barbison	Beneficiation
Tennessee Valley Authority Chattanooga, Tennessee	Thomas Williams	Fly ash production
The Detroit Edison Company Detroit, Michigan	William Arnold	Fly ash production, marketing
The Detroit Edison Company Detroit, Michigan	D. Parker	Operation and maintenance of coal burning power plant equipment
The Detroit Edison Company Detroit, Michigan	F. V. Zimmer	Fly ash production, marketing

Data Source	Primary Contact	Data
Tennessee Valley Authority Knoxville, Tennessee	Robert Cannon Rupert Bullock Alex Ridings Robert Sneed	Fly ash production
Viall-Ohio Fly Ash Company Akron, Ohio	Paul Viall Paul Viall, Jr.	Fly ash production, marketing

B.2 FLY ASH UTILIZATION, SPECIFICATIONS, AND TECHNOLOGY

Data Source	Primary Contact	Data
Alabama Highway Department Montgomery, Alabama	J. A. Hester D. B. Flournoy	Highways and highway specifications
American Concrete Paving Association Oak Brook, Illinois	John Greesaman	Highways and specifications
American Electric Power Service Corporation Charleston, W. Virginia	Ronald E. Morrison	Product development
American Electric Power Service Company New York, New York	S. Marmaross	General utilization
American National Standards Institute, Inc. New York, New York	C. H. Burns	Specifications general utilization
American Technology Exchange, Inc. Esslingen, W. Germany	W. W. Reichert	Foreign technology exchange, gas concrete
Belden Brick Company Canton, Ohio	Burke Wentz	Bricks
Bergbau Forschung, GmbH Essen-Kray, W. Germany	Dr. K.H. van Heek	General utilization

Data Source	Primary Contact	Data
California Highway Department Sacramento, California	John Beaton	Highways and highway specifications
Celcon London, England	Mr. Smit-Hansen Mr. Lucklin	Gas concrete
Central Electricity Generating Board London ECI, England	Alex Wilson Peter Smith	Highway structural fill
Central Research Institute of Electric Power Industry Tokyo, Japan	Yoshimi Ishihara	General utilization
Chicago Fly Ash Company Chicago, Illinois	C. E. Lovewell E. Hyland	Concrete technology
Clawson Concrete Company Detroit, Michigan	Earl Colburn	Lightweight aggregate, ready-mix
Collinwood Shale Brick and Supply Company Cleveland, Ohio	Mr. Maxwell	Ready-mix
Colorado Department of Highways Denver, Colorado	C. E. Shumato	Highway and highway specifications
Commonwealth Edison Company Chicago, Illinois	Joseph McCluskey	Fly ash production
Connecticut Department of Transportation Wethersfield, Connecticut	J. F. Shugrue	Highways and highway specifications
Consolidated Edison Company of New York, Inc New York, New York	William Bannon	Lightweight aggregate and road base course
Consolidated Rock Products Company Los Angeles, California	Everett A. Jumper	Ready-mix

Data Source	Primary Contact	Data
Cooke Contracting Company Detroit, Michigan	Bill James	Asphalt filler
Delta Concrete Company, Arrow Block Company Bellaire, Ohio	John L. Seabright	Ready-mix, concrete block
Dravo Corporation Pittsburgh, Pennsylvania	Arthur Livingood	Ready-mix
Duquesne Light & Power Elrama, Pennsylvania	Larry Clark	Lightweight aggregate
Duquesne Light & Power Pittsburgh, Pennsylvania	J. Jaworski Dan Jospeh	Lightweight aggregate
Edison Electric Institute New York, New York	G. A. Olson	Edison Electric Institute survey
Environmental Policy Division Legislative Reference Service Library of Congress Washington, D. C.	Harry Perry	General utilization
Federal Aviation Agency Washington, D. C.	P. E. Melville	Airport runway construction
Fisher Concrete Company Memphis, Tennessee	R. W. F. Mosby	Ready-mix
Flood Testing Laboratories Chicago, Illinois	Walter H. Flood	Concrete specifications
Florida Department of Transportation Gainesville, Florida	J. D. Gammage	Highways and highway specifications
Freeport Brick Company Elrama, Pennsylvania	W. Kukuk Amil Proto	Lightweight aggregate
Freeport Brick Company Freeport, Pennsylvania	D. J. Stefl	Lightweight aggregate

Data Source	Primary Contact	Data
G. and W. H. Corson Company Plymouth Meeting, Pennsylvania	Dr. L. J. Minnick Tom Atherton	Sintered products, road base materials, concrete admixtures, specifications
Georgia Highway Department Atlanta, Georgia	T. D. Moreland	Highways and highway specifications
H + H Industri A/S Copenhagen, Denmark	Erik Dam Hansen Leo Blaabjerg Søensen	Gas concrete
Highway Ready-Mix Company Dravosburg, Pennsylvania	J. Cutlip	Ready-mix, asphalt filler
Highway Research Board Division of Engineering National Research Council Washington, D. C.	J. W. Guinnee	Highways and highway specifications
Illinois Department of Public Works and Buildings Springfield, Illinois	W. E. Baumann	Highways and highway specifications
Iowa Highway Commission Ames, Iowa	J. R. Coupal, Jr.	Highways and highway specifications
Iowa State University Ames, Iowa	Dr. R. C. Joshi	Synthetic fly ash pozzolanic action
Kuhlman Builders Supply and Brick Company Toledo, Ohio	William E. Brewer	Ready-mix
Marquette Cement Company Chicago, Illinois	Owen Brown	Manufacture of Portland cement
Maryland State Roads Commission Baltimore, Maryland	Nathan L. Smith, Jr.	Highways and highway specifications

Data Source	Primary Contact	Data
Material Service Corporation Chicago, Illinois	Ronald Blick	Ready-mix
McDowell-Wellman Dwight Lloyd Division Cleveland, Ohio	Harold E. Rowen	Lightweight aggregate
Michigan Department of State Highways Lansing, Michigan	R. L. Greenman	Highway and highway specifications
Michigan Institute of Technology Houghton, Michigan	Professor Freiberger	Lightweight aggregate process without sintering
Minnesota Department of Highways St. Paul, Minnesota	F. C. Fredrickson	Highways and highway specifications
Missouri Highway Commission Jefferson City, Missouri	T. E. David	Highways and highway specifications
Missouri Portland Cement Company St. Louis, Missouri	Bruce Kester	Manufacture of Portland cement
National Ash Association Washington, D. C.	John Faber Philip Meikle George A. Kladnik	General utilization
National Asphalt Pavement Association Riverdale, Maryland	Fred Kloiber	Highways and highways specifications
National Ready-Mix Concrete Association Silver Springs, Maryland	D. L. Bloem	Ready-mix
Nello L. Terr Company Flylite Division Charlotte, No. Carolina	Kenneth Nelson	Lightweight aggregate

Data Source	Primary Contact	Data
New Jersey Department of Transportation Trenton, New Jersey	C. E. Kucker	Highways and highway specifications
New York Department of Transportation Albany, New York	M. Tedza	Highways and highway specifications
Niagara Mohawk Power Company Syracuse, New York	Arthur Stefanski	Lightweight aggregate
North Carolina State Highway Commission Raleigh, No. Carolina	M. D. Barbour	Highways and highway specifications
North Dakota Highway Department Bismarck, No. Dakota	R. W. Bradley	Highways and highway specifications
Ohio Department of Highways Columbus, Ohio	G. J. Thormeyer	Highways and highway specifications
Pennsylvania Department of Transportation Harrisburg, Pennsylvania	L. D. Sandvig	Highways and highway specifications
Penn Dixie Cement Company Pittsburgh, Pennsylvania	Charles Seamon	Cement manufacturing
Pit and Quarry Publications Chicago, Illinois	--	Geographic locations - cement and lightweight aggregate plants
Portland Cement Association Skokie, Illinois	Paul Klieger	Fly ash concrete
Purdue University Department of Engineering Lafayette, Indiana	Dr. E. J. Yoder	Highways
Ready-Mix Concrete Company Knoxville, Tennessee	F. H. Pittenger	Ready-mix

Data Source	Primary Contact	Data
Rhode Island Department of Transportation Providence, Rhode Island	M. Chorney	Highways and highway specifications
River Cement Company St. Louis, Missouri	Arthur Hunter	Cement manufacture
Robert Hildebrand Maschinenbau GmbH Nuertingen, W. Germany	Hansjurg Breinbauer	Gas concrete
Skidmore, Owings and Merrill, Architects and Engineers Chicago, Illinois	Harold Iyenger	Concrete specifications
South Carolina Highway Department Columbia, So. Carolina	J D. McMahan, Jr.	Highways and highway specifications
Southwest Portland Cement Company Los Angeles, California	J. L. Goetz	Fly ash in portland cement manufacturing
State Highway Commission of Kansas Topeka, Kansas	Carl F. Crumpton	Highways and highway specifications
Steinkohlen Elektrizitat AG Essen, Germany	H. Nteite	Automatic brick machinery, flyash production
Steinkohlen Elektrizitat AG Essen, Germany	Hermann Erythropel	Fly ash production/ utilization
Stirling Sintering Company South Heights, Pennsylvania	Harold T. Stirling Charles R. Harbison	Lightweight aggregate
Structural Clay Products Institute McLean, Virginia	Richard Otterson	Bricks
Tennessee Valley Authority Knoxville, Tennessee	Robert Cannon Rupert Bullock	Concrete technology

Data Source	Primary Contact	Data
Tennessee Valley Authority Sequoyah Nuclear Power Plant Knoxville, Tennessee	Stanley Carr	Concrete construction
Texas Highway Department Austin, Texas	J. C. Dingwall	Highways and highway specifications
The Asphalt Institute College Park, Maryland	John M. Griffith	Highways and specifications
The Charles Svec Company Maple Heights, Ohio	Charles Svec	Concrete block
The Detroit Edison Company Detroit, Michigan	F. V. Zimmer	Lightweight aggregate, concrete blocks, ready-mix, bricks
The Master Builders Company Cleveland, Ohio	Dr. Richard C. Mielenz	ASTM specifications, chemical admixtures
U.S. Army Corps of Engineers Los Angeles, California	Jack Short	Highways and highway specifications
U.S. Army Corps of Engineers Waterways Experiment Station Vicksburg, Mississippi	Bryant Mather	Specification, concrete admixtures
U.S. Bureau of Mines Engineering Research Center Morgantown, W. Virginia	John Capp	Agriculture, land reclamation
U.S. Bureau of Mines Pittsburgh, Pennsylvania	Malcolm Magnuson	Disposal of fly ash in abandoned coal mines
Valore Research Associates Ridgewood, New Jersey	Rudolph C. Valore, Jr.	General utilization, specifications, and technology

Data Source	Primary Contact	Data
VEBA Kraftwerke Ruhr GmbH Gelsenkirchen-Buer, W. Germany	Wilhelm Schmidt Rudolf Feuser	Lightweight aggregate
Viall-Ohio Fly Ash Company, Inc. Akron, Ohio	Paul Viall Paul Viall, Jr.	Ready-mix, concrete block, and roadways
Waylite Corporation River Rouge, Michigan	Allen Rowen	Lightweight aggregate
West Virginia Department of Highways Charleston, W. Virginia	Joseph S. Jones	Highways and highway specifications
West Virginia University School of Mines, Coal Research Bureau Morgantown, W. Virginia	J. W. Leonard C. E. Cockrell	Brick and mineral wool research
Williams Brothers Concrete Company Atlanta, Georgia	Horace Williams	Ready-mix
Wyoming Highway Commission Cheyenne, Wyoming	D. G. Miller	Highways and highway specifications

B. 3 LIMESTONE-MODIFIED FLY ASH

Data Source	Primary Contact	Data
Combustion Engineering Company Windsor, Connecticut	Dr. William C. Taylor	Limestone-modified fly ash research

Data Source	Primary Contact	Data
Environmental Policy Division Legislative Reference Service Library of Congress Washington, D. C.	Harry Perry	Limestone-modified fly ash production, research and utilization
G. and W. H. Corson Company Plymouth Meeting, Pennsylvania	Tom Atherton	Limestone-modified fly ash for road base course
Kansas City Power and Light Company Kansas City, Missouri	Pat Tansey Mr. Davidson	Limestone-modified fly ash production
Kansas Geological Survey Group Mineral Resources Section Kansas City, Missouri	Ronald D. Hardy	Limestone-modified fly ash production
Kansas Power and Light Company Lawrence, Kansas	Lee Brunton	Limestone-modified fly ash production
Michigan Institute of Technology Houghton, Michigan	Professor Freiberger	Lightweight aggregate
Missouri Portland Cement Company St. Louis, Missouri	Bruce Kester	Limestone-modified fly ash
National Ash Association Washington, D. C.	John Faber	Limestone-modified fly ash utilization
Union Electric Company Merimec #2 Unit St. Louis, Missouri	Mr. Harrington	Limestone-modified fly ash production
Valore Research Associates Ridgewood, New Jersey	Rudolph C. Valore, Jr.	Limestone-modified fly ash utilization
West Virginia University School of Mines Coal Research Bureau Morgantown, W. Virginia	C. E. Cockrell	Limestone-modified fly ash research and utilization

APPENDIX C

BASIC PORTLAND CEMENT CONCRETE PROPORTIONING TECHNOLOGY AND ECONOMICS OF FLY ASH CONCRETE

C.1 GENERAL DISCUSSION

The two basic types of concrete in use today are classified as either non-air-entrained concrete, which has a natural air content range from 0.3 to 3 percent, or air-entrained concrete, which has an air content ranging from 3.5 to 8 percent. The greatest advance in concrete technology in recent years has been the advent of air-entrainment, and today the use of entrained air is recommended in concrete for nearly all industrial and commercial structures (Ref. C-57). The principal reason for using intentionally entrained air is to improve concrete's resistance to freezing and thawing exposure. Non-air-entrained concrete is used mainly for relatively low strength residential structures where the problems related to exposure and other properties are not as severe as on commercial and industrial types of structures.

Figure C-1 (Ref. C-57) indicates the relationship between the compressive strength and curing age of concrete when a Type I portland cement is used. In order for the concrete to develop to its full final strength, it is necessary for moisture to remain in contact with the cement. The strength of the concrete will then follow the solid line indicated on Fig. C-1. If the concrete is not kept moist, and is exposed to air for the respective times indicated on the figure, the full strength is not realized.

The early strength of concrete is of importance in using concrete in that it determines the curing time to reach the required strength before loads can be placed on the concrete. Table C-1 indicates the strength that can be expected from Type I cement after a given curing time. It should be noted that in order to compare fly ash concrete with the conventional portland cement concrete, it will be necessary to obtain approximately equal strength at equal time periods in the curing cycle in order to make a fair comparison of their respective utilization when considering similar design conditions.

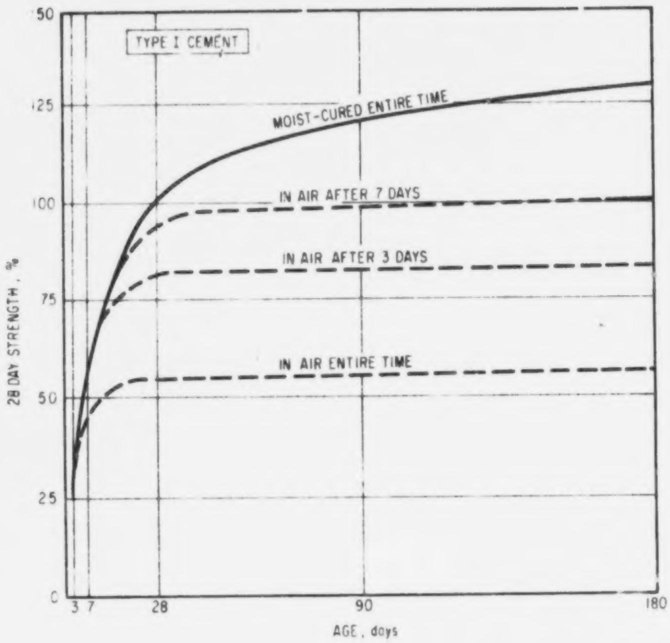

Fig. C-1. Moist Curing of Portland Cement Concrete

Table C-1. Age-Strength Relationship of Air-Entrained Concrete

Age, Type I Cement	Strength, psi
25 hours	500
1-1/2 days	750
3-1/2 days	1500
5-1/2 days	2000

The greatest influence in the strength of the concrete is exerted by the water-to-cement ratio as indicated by Fig. C-2. It can be noted that a considerable variation of strength can exist for a given water-to-cement ratio at any time during the curing cycle. The maximum and minimum bands represent approximately 2 sigma standard deviations from the average value (Ref. C-57).

The ease or difficulty of placing and consolidating freshly poured concrete is called workability. With a given amount of water and cement paste, an increase in the amount of aggregate causes a stiff mix which may require considerable labor in placing and finishing. Concrete should be workable but should not segregate into its original components, nor should it bleed excessively. Bleeding is the movement of water to the surface of freshly cast concrete; and since excessive bleeding may increase the water-cement ratio at the surface, a weak surface layer of poor durability may result. This is of particular importance if finishing operations take place while this excess water is present. Generally, the most economical mix is one that has the highest proportion of aggregate to cement, and yet is workable at the water-cement ratio required for strength, durability, and other properties. The test used to measure the consistency of concrete is called a slump test. This is performed by forming a cone from the fresh concrete. The form is then removed from the fresh concrete cone and is allowed to settle. The measurement of the amount of settling in inches is defined as the "slump" of the concrete.

The durability of concrete is mainly related to its resistance to freezing and thawing, wetness, and temperature changes. As noted previously, the freezing and thawing resistance depends on the amount of air entrained. In addition to this, the water-to-cement ratio of the concrete is also of importance in determining durability. Table C-2 indicates the recommended maximum permissible water-cement ratios for different types of structures and degrees of exposures.

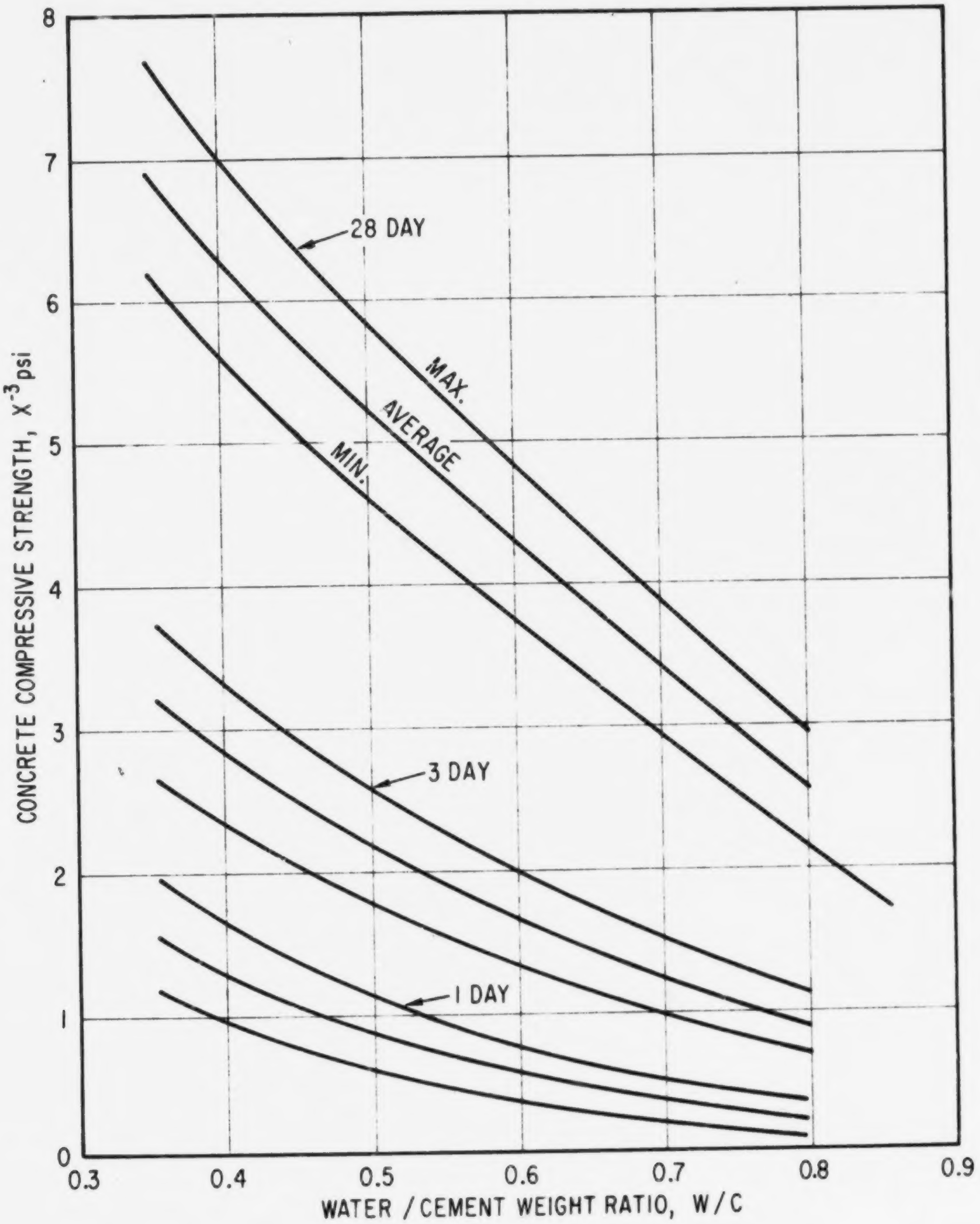

Fig. C-2. Water/Cement - Strength Relation of Concrete

Table C-2. ACI Recommended Maximum Permissible Water-Cement Ratios for Different Types of Structures and Degrees of Exposure[*]

Type of structures	Exposure conditions[**]					
	Severe wide range in temperature, or frequent alternations of freezing and thawing (air-entrained concrete only)			Mild temperature rarely below freezing, or rainy, or arid		
	In air	At water line or within range of fluctuating water level or spray		In air	At water line or within range of fluctuating water level or spray	
		In fresh water	In sea water or in contact with sulfates[†]		In fresh water	In sea water or in contact with sulfates[†]
A. Thin sections such as reinforced piles and pipe	0.49	0.44	0.40	0.53	0.49	0.40
B. Bridge decks	0.44	0.44	0.40	0.49	0.49	0.44
C. Thin sections such as railings, curbs, sills, ledges, ornamental or architectural concrete, and all sections with less than 1-in. concrete cover over reinforcement	0.49	–	–	0.53	0.49	–
D. Moderate sections, such as retaining walls, abutments, piers, girders, beams	0.53	0.49	0.44	††	0.53	0.44
E. Exterior portions of heavy (mass) sections	0.58	0.49	0.44	††	0.53	0.44
F. Concrete deposited by tremie under water	–	0.44	0.44	–	0.44	0.44
G. Concrete slabs laid on the ground	0.53	–	–	††	–	–
H. Pavements	0.49	–	–	0.53	–	–
I. Concrete protected from the weather, interiors of buildings, concrete below ground	††	–	–	††	–	–
J. Concrete which will later be protected by enclosure or backfill but which may be exposed to freezing and thawing for several years before such protection is offered	0.53	–	–	††	–	–

[*] Adapted from Recommended Practice for Selecting Proportions for Concrete (ACI 613-54).

[**] Air-entrained concrete should be used under all conditions involving severe exposure and may be used under mild exposure conditions to improve workability of the mixture.

[†] Soil or groundwater containing sulfate concentrations of more than 0.2 per cent. For moderate sulfate resistance, the tricalcium aluminate content of the cement should be limited to 8 per cent, and for high sulfate resistance to 5 per cent; CSA Sulfate-Resisting cement limits tricalcium aluminate to 4 per cent. At equal cement contents, air-entrained concrete is significantly more resistant to sulfate attack than non-air-entrained concrete.

[††] Water-cement ratio should be selected on basis of strength and workability requirements, but minimum cement content should not be less than 470 lb. per cubic yard.

A low water-to-cement ratio also improves the water tightness of the concrete, and for this reason it is recommended for use in exposures where water tightness or resistance to leakage is of importance.

The testing of the compressive strength of the finished concrete is performed in accordance with a variety of ASTM and Crushed Stone Association specifications. Basically, test specimens consisting of 6-in. diameter by 12-in. high cylinders are made at a rate of two to three cylinders for every 150 yd^3 of concrete produced. The total number of cylinders are then tested for strength and their compressive strength is plotted on a probability plot as indicated in Fig. C-3.

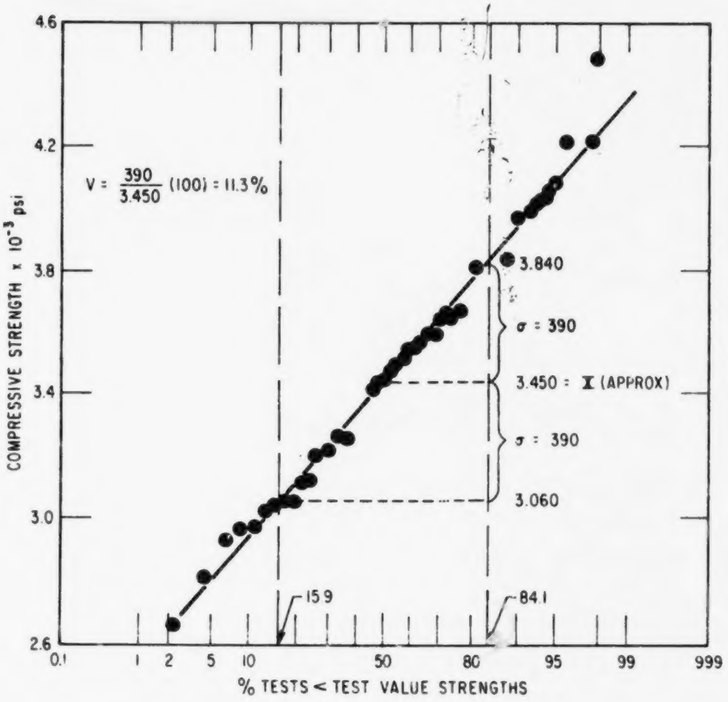

Fig. C-3. Test Results Variations

From this plot the respective standard deviations of the strength of the cylinders from the median strength can be determined, and a coefficient of variation, defined as the ratio of the standard deviation to the value of the mean compressive strength in terms of percentage, is assigned as follows:

$$V = \frac{\Sigma}{X}(100)$$

The relationship between the required average strength of the concrete and the specified strength of the concrete as related to the coefficient of variation can be expressed by the following formula:

$$f_{cr} = \frac{f'_c}{1 - tV}$$

where

f_{cr} = required average strength

f'_c = specified strength

V = forecasted coefficient of variation expressed as a fraction

t = a constant depending upon the proportion of tests that may fall below f'_c and the number of samples used to establish V

If V is established on the basis of a large number of samples (more than 30), $t = 0.842$ for the requirement that not more than 20 percent of the tests may be below f'_c and $t = 1.282$ for the requirement that not more than 10 percent of the tests may be below f'_c. Figure C-4 shows the ratio of required average strength to specified strength for a wide range of values of the coefficient of variation.

To illustrate, assume that specifications require that not more than one test in ten shall be less than a specified design strength of 4000 psi. If the forecasted coefficient of variation is 15 percent, the mix should be designed for an average strength of about 1.25 times 4000, which equals 5000 psi.

Figure C-4 shows the relationship between the required average strength of the concrete and the coefficient of variation for a given allowable number of specimens that are allowed to fall below the specified strength value as determined by a statistical analysis.

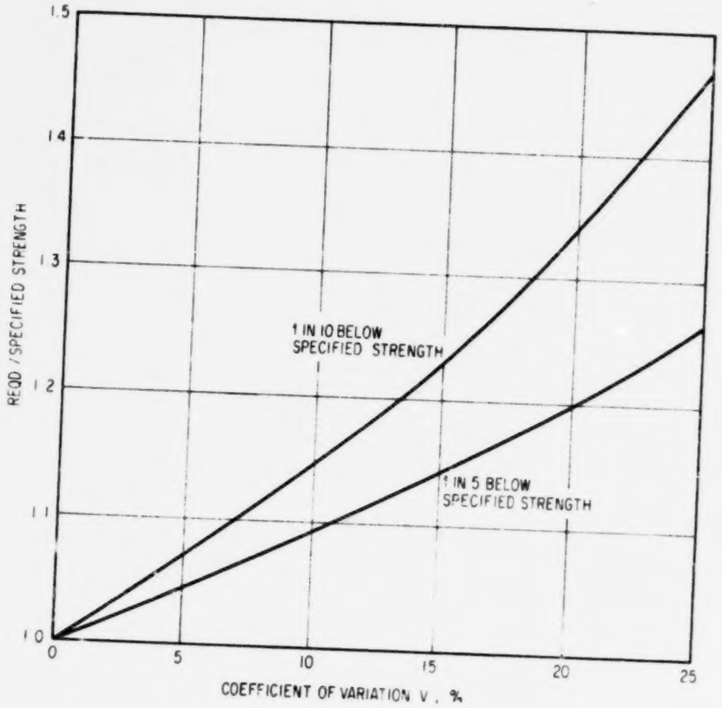

Fig. C-4. Design Requirements

Table C-3 collects the standards of concrete control as expressed in terms of the expected coefficient of variation. Many users of concrete use coefficients of variation in the area of 15 percent and allow from 10 to 20 percent of the test specimens to fall below the specified strength value, thereby utilizing ratios of required-to-specified strength of 1.15 to 1.25.

Table C-3. Standards of Concrete Control

	Coefficient of Variation - Percent			
	Excellent	Good	Fair	Poor
Variation Within Large Number Projects				
Field Control of Tests	10	10-15	15-20	20
Laboratory Control of Tests	4	5-7	7-10	10
Variation Within Single Project/ Single Class Concrete				
Field Control of Tests	4	4-5	5-6	6
Laboratory Control of Tests	3	3-4	4-5	5

As noted previously, the strength of the concrete is determined by the water-to-cement ratio and is generally based on the minimum predicted strength (as shown in Fig. C-2), if no tests are intended to be conducted. In general, it would be expected that the actual strength of concrete produced by proportioning the water-to-cement ratio in this manner would be considerably higher than the minimum. However, the water-to-cement ratio can be increased only if tests are conducted in accordance with the previously described procedure. These tests would be based on producing a trial mix using test cylinders. By evaluation of the data obtained from this, the ratio of water to cement can be altered to arrive at the required water-to-cement ratio for the particular coefficient of variations obtained as a result of the tests.

The proportioning of portland cement concrete mixes are generally based on the specified strength, slump, and air content of the concrete. The general procedure is specified in ACI 613-54 "Recommended Practice for Selecting Proportions for Normal Weight Concrete." The amount of water to be used in the mix is determined from a table similar to Table C-4, and is a function of the maximum aggregate size, slump, and whether the concrete is non-air-entrained or air-entrained.

Table C-4. Amount of Water in Concrete Mixes

	Aggregate Size (in.)						
Non-Air-Entrained Concrete	3/8	1/2	3/4	1	1-1/2	2	3
Slump 1 in. to 2 in.	350	335	315	300	275	260	240
Slump 3 in. to 4 in.	385	365	340	325	300	285	265
Air Content, Percent	3	2.5	2	1.5	1	0.5	0.3
Air-Entrained Concrete							
Slump 1 in. to 2 in.	305	295	280	270	250	240	225
Slump 3 in. to 4 in.	340	325	305	295	275	265	250
Air Content, Percent	8	7	6	5	4.5	4	3.5

As an example for a maximum aggregate size of one inch, an allowable slump of 3 to 4 in., and for non-air-entrainment, it would require 325 lb of water per yd^3 of concrete.

The amount of portland cement required to produce a given strength is computed with the combination of the amount of water and water-to-cement ratio:

$$C = \frac{W}{W/C}$$

As an example, 3000-psi concrete requires a water-to-cement ratio of approximately 0.69 (ACI 613.54) for non-air-entrained concrete. The amount of cement for the previously referred to aggregate sizes, slump values, and air contents are determined by dividing the required 325 lb/yd^3 of water by 0.69, resulting in approximately 470 lb/yd^3 of portland cement.

The amount of coarse aggregate required per yd^3 of concrete increases as the maximum size of the aggregate increases and also increases with the fineness of the fine aggregate. This requirement is mainly related to obtaining a satisfactory workability of the concrete. The range of amounts varies from approximately 1300 lb/yd^3 for a maximum size of 3/8 in. of the coarse aggregate to 2100 lb/yd^3 for a maximum 1-1/2 in. size aggregate using a medium size fine aggregate.

The amounts of fine aggregate are determined on the basis of the maximum size of the coarse aggregate, and range from 1200 lb/yd^3 for 3/8 in. maximum size coarse aggregate to 900 lb/yd^3 for 1-1/2 in. maximum size coarse aggregate.

During 1969, the total United States concrete ready-mix production was 186 million yd^3/yr. This was produced by approximately 5400 companies and resulted in an average production per company of 35,000 yd^3/yr. It is estimated that the median production company, i.e., company number 2700, produced approximately 14,000 yd^3 annually. Figure C-5 shows the distribution of production in terms of percent of concrete produced by the ready-mix concrete companies.

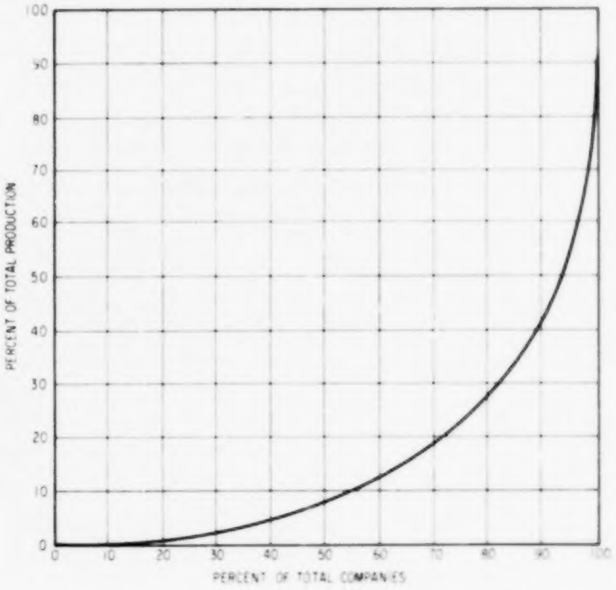

Fig. C-5. Concrete Production Distribution

It can be seen that 90 percent of the 5400 companies produced approximately 40 percent of the total concrete and that the upper decile companies produced 60 percent of the concrete, amounting to approximately 110 million yd^3. Figure C-6 shows the percentage breakdown of the uses to which the ready-mix was applied and also indicates the type of concrete that is used in general for the particular types of uses shown. It can be noted that approximately 30 percent of the concrete is used for residential and farm construction which is usually lower strength, with lesser requirements on durability, and can utilize non-air-entrained concrete. The remaining 70 percent are mainly industrial or commercial, and would in almost all cases use air-entrained concrete. It can therefore be deduced that as a maximum, 30 percent of the total production of 186 million yd^3, or approximately 55 million yd^3 is non-air-entrained and is used mainly in the 2500 to 3500 psi range.

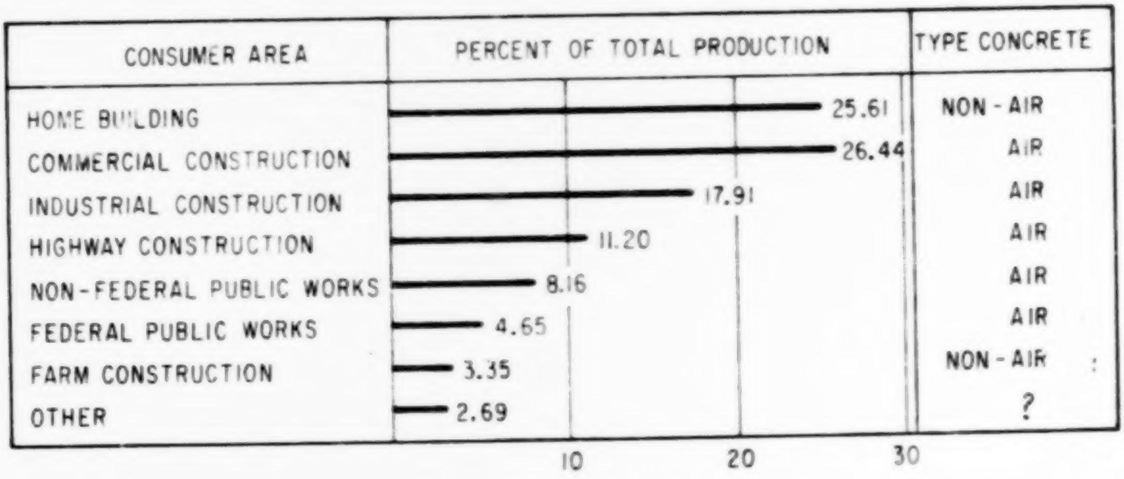

Fig. C-6. Ready-Mix Concrete Consumption

C.2 ECONOMIC ANALYSIS OF FLY ASH NON-AIR-ENTRAINED CONCRETE

An economic analysis of non-air-entrained fly ash concrete was conducted using the ACI proportions for Mix C (See Table 4-5). The ground rules used for this analysis are explained in the following discussion. At the end of the example, the effects of varying the input parameters is given; that is then followed by a discussion of the effects of air entrainment.

In this example, the value used for the cost of Type I cement was \$22/ton, equal to 1.1 cent/lb as delivered to the ready-mix concrete producer. The cost of the fly ash F.O.B. utility was expressed in parametric form at 2, 4, 5, and 6 dollars/ton, equivalent to 0.1, 1.2, 1.25, and 3.0 cents/lb, respectively. The cost of transporting the fly ash from the utility to the ready-mix concrete producer was obtained from a variety of fly ash sellers and users and is shown in Fig. C-7. This is based on a \$2.00 handling charge plus variable transportation costs ranging from zero to \$2.00 up to 65 miles. After a distance of 65 miles from the utility to the ready-mix producer, the cost was estimated at a straight \$0.06 per ton/mile.

Since the use of fly ash by the ready-mix concrete producer requires additional equipment such as storage bins, handling equipment, and dust removal equipment, a certain amount of capital investment and maintenance is involved on his part to use fly ash for the production of ready-mix concrete. It was estimated that the ready-mix concrete producer would have a production capacity of approximately 35,000 yd^3, and that he would use in the area of 2000 tons of fly ash annually. Based on discussions with various ready-mix concrete producers and fly ash brokers, it was concluded that this would require an average investment of about \$17,500. This was assumed to be amortized over a time period of approximately five years, resulting in a capital investment cost of \$3500 annually, Financing, if any, was ignored due to the rough order of these approximations. To the \$3500 would be added an annual maintenance cost of approximately \$2000, since fly ash has a variety of damaging effects on equipment, requiring a considerable amount of maintenance.

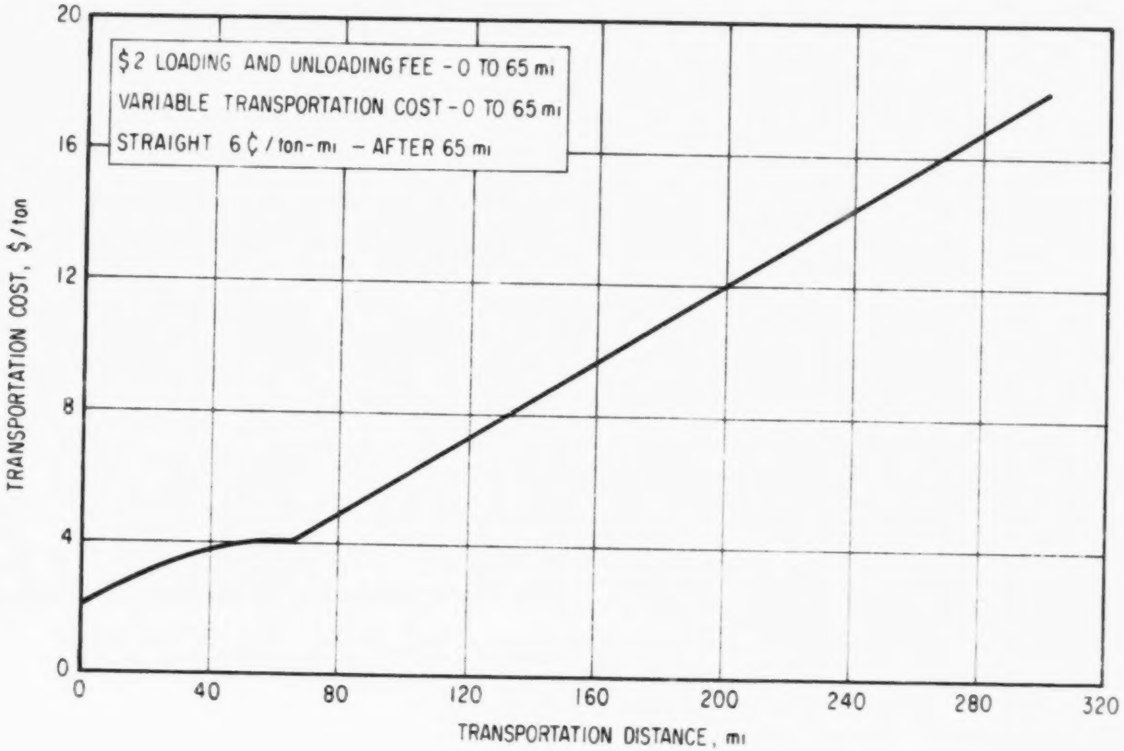

Fig. C-7. Fly Ash Transportation Cost

The resulting cost of the capital investment and maintenance was estimated at $2.80/ton of fly ash. For the respective amounts of 125 lb of fly ash and 75 lb of fly ash/yd^3, the cost would be 17 cents and 10 cents per yd^3.

Table C-5 shows the economic factors which lead to the development of a comparison of the cost of conventional concrete using portland cement, with concrete using a mixture of fly ash and portland cement made to the ACI proportions.

Table C-5. Economic Factors (Non-Air-Entrained Concrete, 1-in. Aggregate, 4-in. Slump, Type I Cement)

Concrete 28-Day Strength, psi	Convent. Concrete				Fly Ash Concrete								
	Cement "C"		Cement "C_m"			Fly Ash $/ton-FOB Utility				Transport Miles			I + M
						2	4	5	6	65	150	300	
	lb/yd³	$/yd³	lb/yd³	$/yd³	lb/yd³	$/yd³				$/yd³			$/yd³
2500	423	4.65	353	3.88	125	0.125	0.25	0.31	0.37	0.25	0.56	1.12	0.17
3000	470	5.16	400	4.40	125	0.125	0.25	0.31	0.37	0.25	0.56	1.12	0.17
3500	517	5.69	446	4.90	125	0.125	0.25	0.31	0.37	0.25	0.56	1.12	0.17
3750	540	5.94	494	5.43	75	0.075	0.15	0.19	0.22	0.15	0.34	0.68	0.10
4000	564	6.20	517	5.68	75	0.075	0.15	0.19	0.22	0.15	0.34	0.68	0.10
5000	659	7.25	611	6.72	75	0.075	0.15	0.19	0.22	0.15	0.34	0.68	0.10

As an example, for the 3000-psi non-air-entrained concrete, the pure portland cement concrete would require 470 lb of portland cement costing $5.16. The fly ash concrete would require 400 lb of portland cement per yd^3 at a cost of $4.40 resulting in a savings for the cost of the portland cement of $0.76. The savings as a result of using the fly ash would be diminished by the cost incurred in buying, using, and transporting the fly ash. This is shown in parametric fashion in Table C-5. Since 3000-psi concrete requires 125 lb/yd^3 of fly ash, the cost of the fly ash/yd^3 of concrete as bought at $2.00/ton from the utility, would be 12.5 cents/yd^3. If it were bought at $6.00/ton, the cost per yd^3 would be $0.37/yd^3, etc. To this would have to be added the cost of transportation, which would be $0.25/yd^3 to transport for a distance of 65 miles and $1.12/yd^3 to transport for a distance of 300 miles. Additionally, the previously discussed capital investment and maintenance cost would have to be added at $0.17/yd^3.

Figure C-8 shows the economics of the 2500 to 3500 psi fly ash concrete relative to pure portland cement concrete for a variety of transportation distances. Discussions with several contractors have shown that the \$4.00/ton F.O.B. utility cost is a typical value and will therefore be used as an example to indicate the economics. It can be seen that if the ready-mix producer is located extremely close to the utility, essentially no transportation costs, but only handling costs, are involved. A savings of approximately \$0.22/yd^3 can be realized. At a distance of approximately 90 miles, the fly ash concrete would break even with the portland cement concrete under the conditions of this example.

The same data are shown for 3750 to 5000-psi concrete on Fig. C-9. It can be seen that with the producer extremely close to the utility, the \$4.00/ton F.O.B. utility fly ash produces a savings of approximately \$0.20 or almost the same as the 2500 to 3500-psi concrete. The break-even distance is somewhat further than for the lower strength concrete, namely at 120 miles, showing that at longer distances the higher strength fly ash concrete can be more economical than the lower strength concrete. This can be attributed to the fact that for the ACI proportions, the higher strength concrete requires less fly ash and therefore less mass would have to be transported. The greater savings for the higher strength are however almost purely academic for non-air-entrained concrete, since this type of concrete is used mainly in the 2500 to 3500-psi range.

The foregoing analysis is parameterized such that varying conditions can be assumed to determine varying economic results. A further refinement could include the parameterization of investment, maintenance, and portland cement costs; however, it is a simple matter to vary these items using the data given in Table C-5. In the basic example, to produce 28-day, 3000-psi non-air-entrained fly ash concrete, it was determined from Table C-5 that, for a ready-mix dealer selling 35,000 yd^3 of concrete per year, 65 miles from the utility, using fly ash at \$4.00/ton F.O.B. utility, portland cement at \$22/ton, paying hauling costs per Fig. C-7, and having an additional

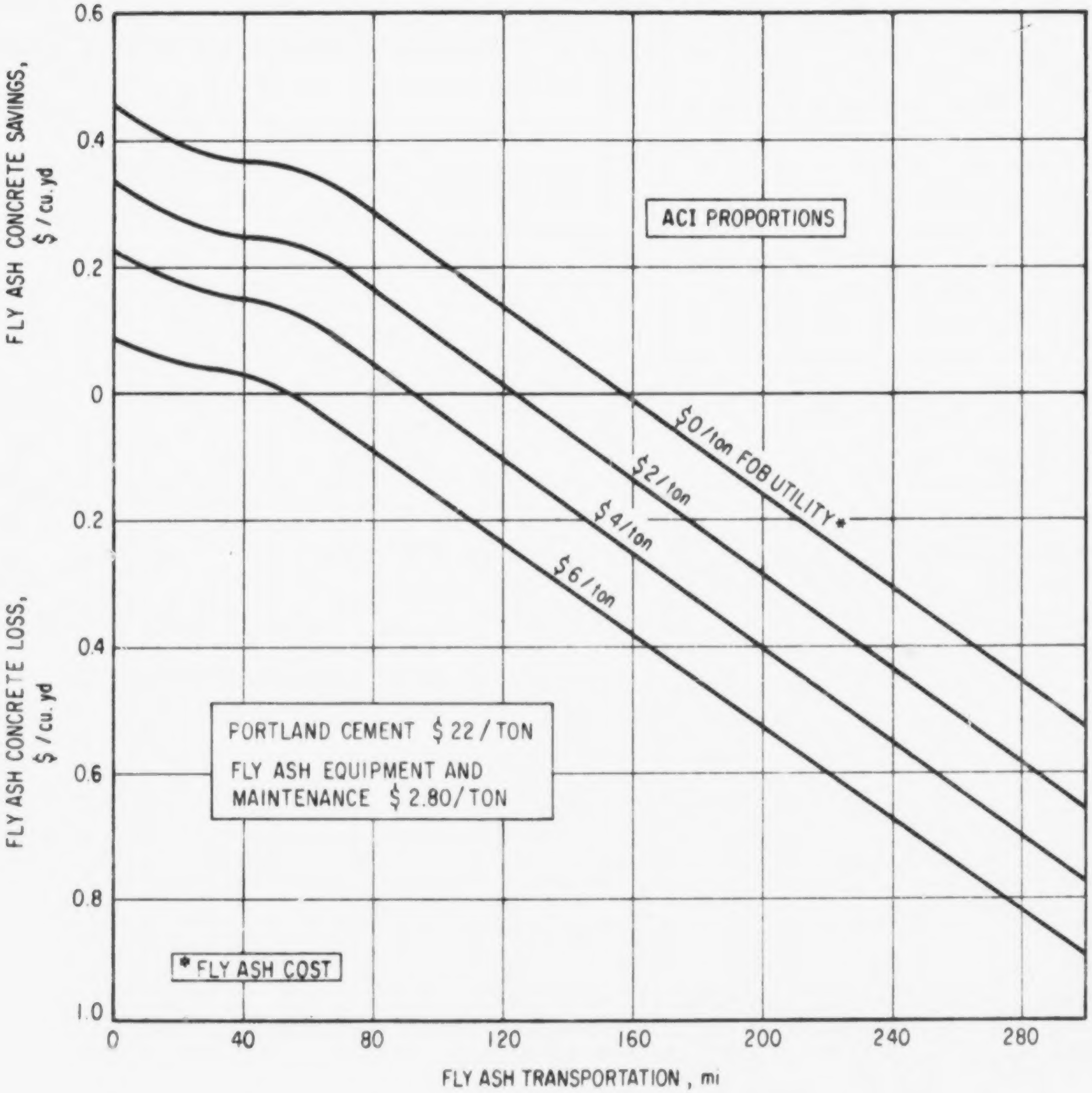

Fig. C-8. Fly Ash Concrete Economics, 2500-3500 psi

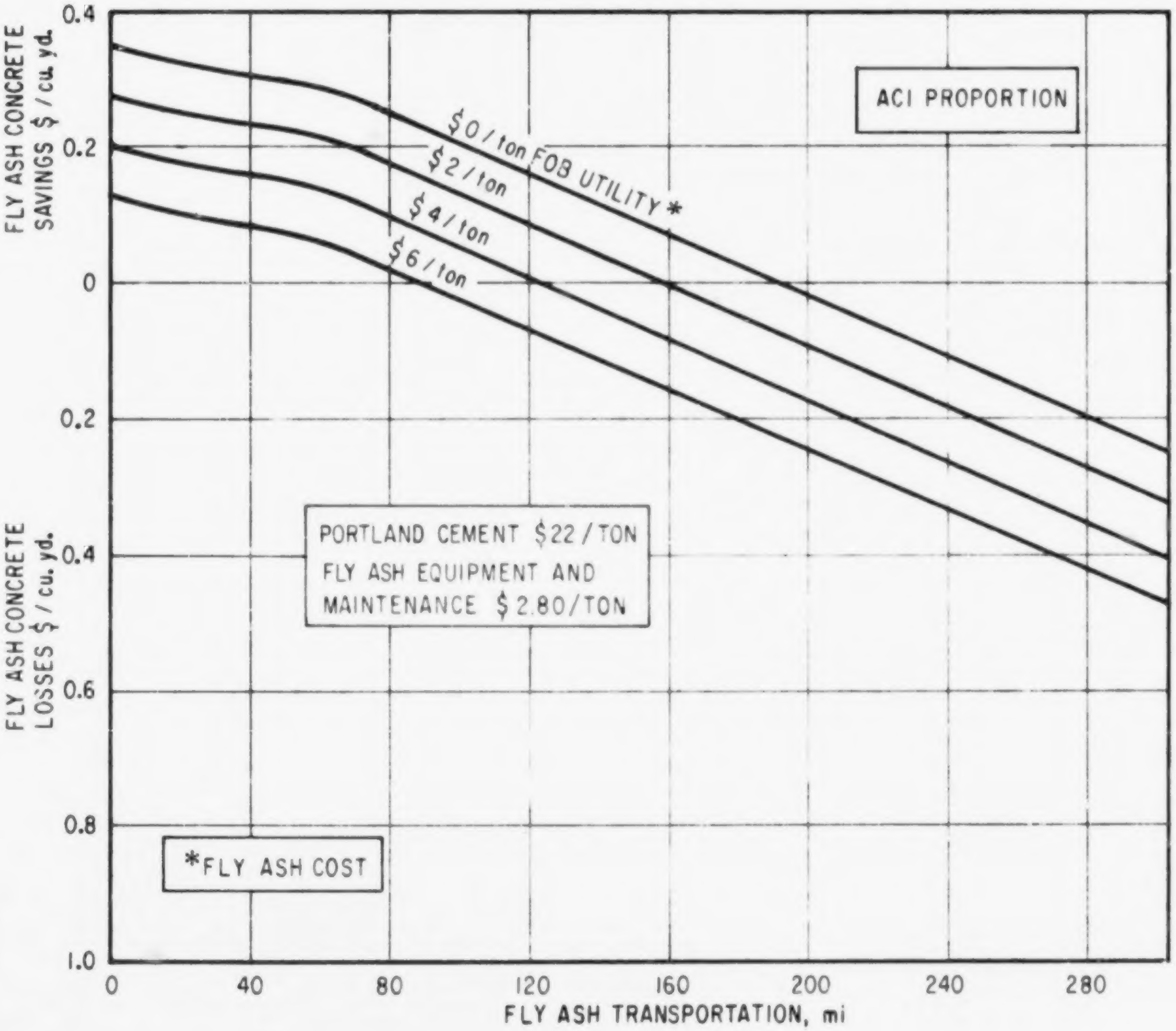

Fig. C-9. Fly Ash Concrete Economics, 3750-5000 psi equipment and maintenance cost of \$2.80/ton, the cost reduction is 9 cents/yd^3. Varying some of the parameters, it can be shown that large savings can be had if the ready-mix dealer is 10 miles from the utility, pays \$26/ton for portland cement and \$2/ton fly ash F.O.B. utility plus hauling costs per Fig. C-7, and reduces the additional equipment and maintenance cost by one-half to \$1.40/ton of fly ash (through less costly equipment investment) the reduction in concrete cost is 53 cents/yd^3. There are, of course, numerous combinations of conditions because of the many significant parameters involved.

The results of several examples, derived in the same manner as those above, are given in Table C-6. The economics favorable to the use of fly ash in this instance are apparent. Effects of variations in proportioning, cure time and air entrainment are discussed later.

Table C-6. Example Cost Variations of Fly Ash Concrete Compared to Portland Cement Concrete (28-Day, Non-Air-Entrained, 3000-psi Concrete)

Fly Ash Concrete (ACI Proportioned) Example Cases	A	B	C	D	E	F
Cement Cost - \$/ton	22	26	26	26	25	25
Fly Ash Cost - \$/ton F.O.B. Utility	4	4	2	4	4	4
Transportation Distance	65	100	10	150	150	65
Added Investment and Maintenance Cost - \$/ton Fly Ash	2.80	2.80	1.40	1.40	1.40	2.80
Cost Variation - Cents/Yd^3 Compared to Portland Cement Concrete Cost	-9	-11	-53	0	+3	-21
Example: If dealer earns \$1.00/yd^3 before taxes on portland cement concrete, his profit impact for cases C and E is +53% and -3%, respectively. If he earns \$3.00 on portland cement concrete, the impact for these two cases is +18% and -1%, etc.						

C. 3 ECONOMIC ANALYSIS OF FLY ASH AIR-ENTRAINED CONCRETE

The application of fly ash in concrete is recognized to have a depressive effect on entrained air content and makes field control of air contents more difficult. Fly ash carbon has been shown to have the capability for adsorbing the organic substances of which most air-entraining agents (AEA) are composed. Depending on the carbon content, some fly ashes in concrete mixtures may require increasing the amount of air-entraining agent as much as four times or more than needed with mixes not incorporating fly ash (C-126). However, on the basis of the chemical content of available fly ash samples discussed in Section 4.3, an average carbon content of four percent is assumed for purposes of the present economic analysis. It is also conservatively estimated from data presented in Ref. C-126 that ready-mix concrete containing four percent carbon fly ash will require twice as much air-entraining agent as needed in conventional concrete mixes. This information coupled with the detailed mix and strength data presented in Ref. C-120 and the ACI proportions shown in Table 4-5 was used to formulate the economic factors that permit a comparison of conventional air-entrained concrete using portland cement with air-entrained concrete using a mixture of fly ash and portland cement. The resulting proportions for the two mixes are shown in Table C-7.

Table C-7. Air-Entrained Concrete

1-in. Aggregate, 34 Total Gallons Water,
4-in. Slump, 5 Percent Air-Entrainment

28-Day Strength Concrete, psi	Cement + AEA		Cement + Fly Ash* + AEA		
	lb	fl oz	lb	lb	fl oz
2500	423	4.5	353	125	9.0
3000	470	5.0	400	125	10.0
3500	541	5.0	494	75	10.0
3750	588	5.0	541	75	10.0

*4 Percent Carbon Fly Ash

The costs for cement, fly ash, transportation, capital investment and maintenance for additional facilities and equipment to utilize fly ash as an additional ingredient in concrete mixes are assumed to be the same as those applied in the foregoing economic analysis for non-air-entrained concrete. The only significant cost difference between these mixes and those shown for non-air-entrained concrete in Section 4.2.1.1.2 is the cost of the air-entrainment agent. The cost of this agent is estimated at 4 cents/oz when used in proportions shown in Table C-7. This indicates that air-entrainment agents for the mixes shown increased the cost of the 4 percent carbon-fly ash concrete by approximately 20 cents/yd^3 when compared to non-air-entrained concrete, and neglects minor effects of water reducer agent requirements and sand proportioning. Referring to Table C-6 it can be shown that the cost impact of air entrainment can be determined by increasing the cost of fly ash concrete in each case by 20 cents/yd^3, which results in a net cost increase of as much as 20 cents/yd^3 in some cases, and a net cost decrease as much as 33 cents/yd^3 in another. This is not considered to be an inhibition to the use of fly ash as described, based on several contacts made in the industry.

It is to be emphasized that the foregoing results are based on the assumption that the fly ash composition contains about four percent carbon. Air-entrained concrete with fly ash containing higher carbon contents will become increasingly less economical in comparison to the conventional portland cement concrete. And, air-entrained concrete containing fly ash with less than four percent carbon content will become more economical until finally fly ash with a carbon content of one percent or less generally requires the same quantity of air-entraining agents as the pure portland cement concrete mix for a given air content.

These estimations of fly ash concrete economics, although not performed in extensive detail, are believed to be sufficient to highlight the more pertinent factors involved in costs. As noted, the economics vary considerably depending on many parameters, but in any event, the superior qualities of fly ash concrete can be obtained in an economical manner, and in many cases the cost of production is less than that for portland cement concrete.

More importantly, in consideration of the utilization of "greater-than-28-day" design strengths, as described in Section 4.4.2.1, the production costs of fly ash concrete (based on today's marketing) can be reduced rather dramatically. Using this technology where applicable, cost reductions can be had for any type of concrete, and for some it can be well in excess of one dollar per yd^3.

APPENDIX D

DESCRIPTION OF TWO FLY ASH LIGHTWEIGHT AGGREGATE PLANTS

There are only two operating lightweight fly ash aggregate plants in the United States; a third is attempting to resume operations after having been shut down. One significant inhibition to the use of fly ash is the difficulties encountered in the manufacturing processes. The following description of the two operating plants provide an insight into some of the critical problems associated with the production of lightweight fly ash aggregate that have been and are being faced.

The first plant discussed obtains its fly ash from three power plants, one of which is less than a mile away. At these power plants, the fly ash is transported from collecting hoppers to storage silos, dampened (7 to 9 percent) and loaded out by truck. If, for any reason, the aggregate plant cannot receive the ash from these storage silos, the trucks proceed to a dumping site maintained by the utility. Normally, the dampened fly ash is dumped at the lightweight aggregate plant into a below-grade hopper. Figure D-1 illustrates the flow for production fly ash aggregate by this process. The process is initiated by elevating fly ash from the hopper by conveyor and placing it into one of the five bins depending upon its power plant origin.

Withdrawal from the bins is volumetrically controlled by a variable speed belt feeder. There is considerable "rat-holing" in these bins despite 70° sloping sides and relatively large bottom openings. This is overcome through operation of automatic, sequentially programmed, expanding rubber panels mounted on the bin walls and by use if air vibrators.

The fly ash is next conveyed to a mill where a blending of the different

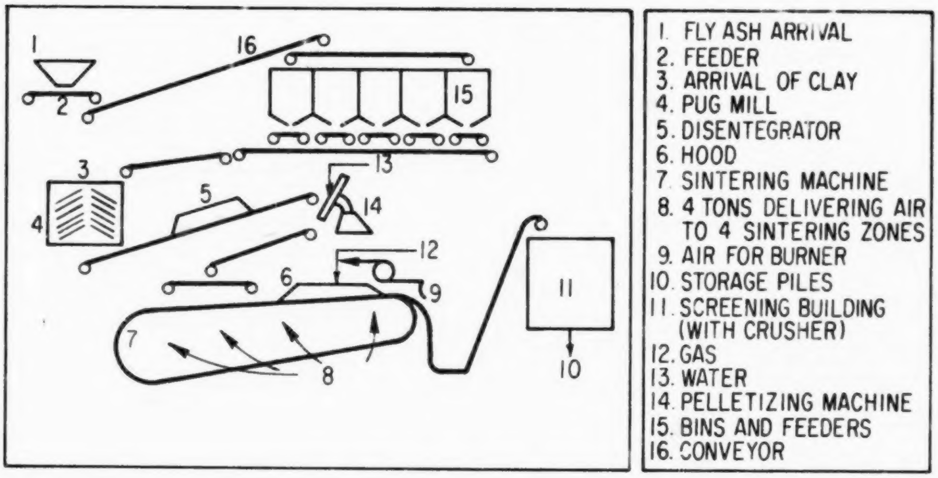
1
16
2
15
3
13
5
14
4
12
6
9
11
7
8
10
1. FLY ASH ARRIVAL
2. FEEDER
3. ARRIVAL OF CLAY
4. PUG MILL
5. DISENTEGRATOR
6. HOOD
7. SINTERING MACHINE
8. 4 TONS DELIVERING AIR TO 4 SINTERING ZONES
9. AIR FOR BURNER
10. STORAGE PILES
11. SCREENING BUILDING (WITH CRUSHER)
12. GAS
13. WATER
14. PELLETIZING MACHINE
15. BINS AND FEEDERS
16. CONVEYOR

Figure D-1. Fly Ash Lightweight Aggregate Production Flow

types handled takes place. Two other ingredients, clay slip (slurry), and dry fly ash, are added at this point and provide the key to this particular process in compensating for variances in the fineness and carbon content of the fly ash received from the various power plants. To compensate for these variances, a small amount of high-carbon-content fly ash obtained from a nearby industrial plant is added, and as much clay slip as the moisture content of other incoming raw materials will permit is used. The amount of clay slip required at the mill is metered out of a trough by a feeder. The speed of the feed is controlled by the shift operator, depending on the moisture needs. After the clay slip has been mixed with the fly ash in the mill, the resulting material is conveyed through a lump disentegrator, then to a pelletizer where 3/4 to 3/16 inch pellets are produced. Moisture needs are determined by observing the ball size and consistency in the pelletizer. The practical limits of the pellet size is governed by the need for proper firing of the pellets from shell to core. The pellets are spread by a swinging conveyor onto an 8 by 102-foot-long sintering machine. They contain about 25 percent moisture and must be dried slowly enough to avoid excessive condensation in the lower parts of the 8 to 10-inch deep sinter bed. Approximately one-fourth of the sintering machine is used for drying.

After drying, the hardened pellets with a carbon content of about 5 percent are ignited and burned, while a surface temperature of 1900 to 2100°F is maintained on the pellet bed by overhead gas burners. After firing, the pellets are air cooled, then lightly sprayed with water to lay the dust, then discharged for immediate crushing and screening into the desired sizes.

This plant normally operates three shifts a day, 5 days a week. Fourteen men normally are employed to operate the day shift, with two men employed on both the afternoon and night shift. All maintenance, clean-up, clay slip preparation, and loading-out of product take place on the day turn only. The design capacity of the lightweight aggregate plant is 1000 tons/day. Present yearly production averages about 500 tons/day, or 135,000 tons/yr.

During the planning of this particular operation, it was originally assumed that the anticipated variation in physical properties and carbon content of the fly ash could be overcome through equipment design and operation alone. However, it was found after a short period of operation that changes in the fly ash, which could not be detected with equipment and personnel available at the plant, were having such a radical effect on balling and firing that at times a usable aggregate could not be manufactured. At this juncture, the assistance of the utility was requested and obtained whereby the power plants furnishing fly ash established a sampling program in which the analysis of ash samples during periods of good and bad operation was provided. This program resulted in the determination that the sintering plant failed to function satisfactorily whenever the combustible content of the fly ash feed fell below 4 percent, or when the percentage of particles below 5 microns in the feed was less than 15 percent.

During this period, a number of alternatives were considered to solve the problem. Most were discarded due to excessive equipment or operating costs for additional processing steps or additives. Grinding of the fly ash was considered, but it was found that improvement obtained in particle size was not significant from any reasonable amount of grinding. Also, it was found that size separation, with disposal of the larger fractions, was not feasible due to the large amount of material that would be lost. After considerable deliberation and in-plant testing, it was decided to use local surface clay and high-carbon fly ash as additives. While the initial cost for handling equipment would be higher than for other additives, the purchase and preparation costs for local clay and high carbon fly ash would be low enough to pay for themselves. It was concluded that the added provisions for accepting clay slip and high-carbon fly ash in this process rendered the operation less sensitive to changes in the fly ash feed, and minimized the danger of producing unusable material.

The second fly ash sintering plant was originally designed to accommodate the entire fly ash output from a single power station. Initially only two of the four sintering machines were installed. By eventually utilizing four sintering machines, the output will be adjusted to meet demand. Flexibility in the balance of the material handling equipment is achieved through a complete system of conveyors, crushers, screens, and bins.

The material flow for this plant can be traced by referring to Figure D-2 . Beginning at the power plant fly ash silo, fly ash flows to the prescreening building via a series of air slides. The screens remove particles larger than mesh size (120), with the balance of fly ash pneumatically conveyed

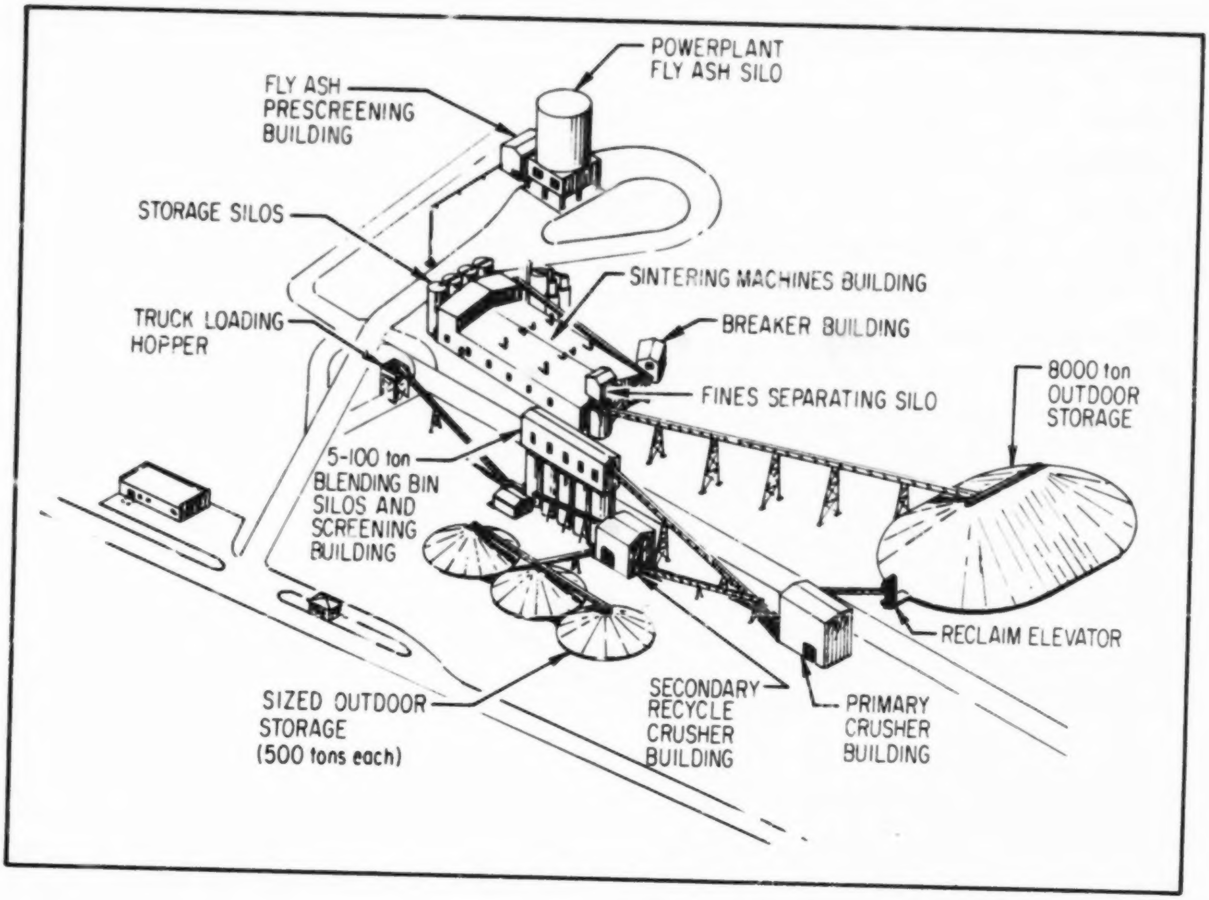
POWERPLANT FLY ASH SILO
FLY ASH PRESCREENING BUILDING
STORAGE SILOS
SINTERING MACHINES BUILDING
TRUCK LOADING HOPPER
BREAKER BUILDING
8000 ton OUTDOOR STORAGE
FINES SEPARATING SILO
5-100 ton BLENDING BIN SILOS AND SCREENING BUILDING
RECLAIM ELEVATOR
SIZED OUTDOOR STORAGE (500 tons each)
SECONDARY RECYCLE CRUSHER BUILDING
PRIMARY CRUSHER BUILDING

Figure D-2. Fly Ash Lightweight Aggregate Production - Material Flow to the 75-ton-capacity storage silos which have an automatic dust filter system. Special mixers in the sintering building receive fly ash through a screw conveyor from the storage silo. This particular portion of the building is designed so that magnetic separators may be installed for iron recovery if desired in the future.

Fly ash, water, return sinter fines and binder are mixed together and the conditioned material is fed by screw conveyor and belt conveyor to the extruder. Fly ash is forced through a die plate by an extruder auger. Strands of varying diameters can be produced simply by changing dies, although 1/4 to 1/2 inch is normal. Pellets are formed as the emerging strands are cut to the desired length by rapidly rotating blades. The pellets drop onto a special screening feeder which feeds onto the sintering machine pallets. The pallets, which are 12 X 16 X 16 inches in size are specially designed to permit uniform heat treatment and penetration of the air into the bed. Fines which pass through the screening feeder are returned to the mixing bin by conveyor belt.

A hydraulic piston type pusher is used to move the entire line of pallets at the desired speed. After the piston reaches its limits of travel, it returns to engage another pallet returning on the curved overhead track.

As the pallets are filled to the proper bed depth, they pass over the preheat section where pellets are dried using waste heat from the cooling section of the machine. The bed then passes over the enclosed burner section, where the bottom 3 to 4 inches is ignited by a series of burners, then over a series of wind boxes which control the rate with which the fire layer moves up through the bed until firing is completed.

When the pallet reaches the end of the machine, the pallet is lifted up and away from the machine, spilling the pellet clusters back onto a 30-inch conveyor. The empty pallet is then deposited on the overhead return track to begin the cycle over again. A dust collecting system is provided for the pan conveyor area.

The pan conveyor takes the pellet clusters to a spiked single-roll breaker which separates the pellets that have become fused together. From here, the pellets are moved via pan conveyor to a high-temperature screen where minus ten mesh particles are removed and returned to the 10-ton fines bin where 5 to 10 percent of sintered fines is added to the raw fly ash at the mixer. This is controlled by bin indicators which activate the feeders and conveyors automatically. The sinter not passing through the screen is conveyed to the 8000-ton-capacity outdoor stockpile.

Sintered aggregate is reclaimed by an under-pile conveyor which is fed by six vibrating feeders. From the storage pile, material is fed by a bucket elevator and conveyor to the primary crushing and screening station. The primary crusher and screen is so arranged that part or all of the material may be by-passed around the crusher directly to the final screening stations and then the storage silos. Double-deck screens, 4 by 12 feet in size, separate the material received from the crusher into five size fractions and deposit them selectively into 100-ton blending bins. The four coarse bins can be recycled should finer aggregate be required; thus, it is possible to adjust each size fraction according to market conditions without costly rehandling of excessive fines.

Provisions for blending any combination of the five sizes is accomplished through feeders on each storage bin, which simultaneously and automatically weigh out the correct amount of each size fraction onto the load-out belt conveyor. Blended aggregate can be fed directly to a truck hopper with the total weight of the shipment measured through a belt scale.

Additional finished product storage is provided by three outdoor storage piles fed by a system of conveyors from the silos. This material may be loaded into trucks by a front-end loader for delivery to the customer.

In addition to the original capital investment, this plant has experienced considerable additional expenses in the redesign, modification, development and fabrication of the various portions of the originally installed sintering equipment. This additional investment and the plant downtime that resulted has contributed greatly to excessive production costs.

As an indication of the technical problems and expense that have been experienced with the sintering equipment, the grates represent a good example. Each sintering machine contains 338 individual grates. The original grates burned out at varying times, but only averaged approximately 500 hours of operation. The replacement cost of each original grate was $30 in addition to the shutdown time required for replacement. A new grate has been developed which will operate for about 2500 hours before replacement is necessary at a cost of about $15 each.

This plant operates three shifts per day, 5 days a week, with a total of 22 employees. With two currently operational sintering machines, it has a maximum capacity for producing 360 tons/day of lightweight fly ash aggregate. This production can be doubled with the planned installation of two additional sintering machines. The plant also includes a well-equipped testing laboratory in which tests are conducted on the fly ash raw material, green pellets, and final aggregate as well as on products manufactured from the aggregate.

APPENDIX E

CEMENT PRODUCTION PLANT UTILIZING FLY ASH

The following figure, derived from Refs. C-57, C-116, and C-117, shows the general processing at the Missouri Portland Cement Company plant in Joppa, Illinois. The limestone and sandstone are brought by 3000-ton barges from the quarry site to the cement plant. Automatic unloading systems unload the limestone and sandstone from the barge and mechanical conveyors move this material to storage facilities. (See Fig. E-1.)

The fly ash presents some special handling problems. It is conveyed pneumatically through a 7500-ft pipe from the utility to an 800-ton storage tank. The tank is equipped with bottom aeration to prevent packing. To minimize flushing, which is always a problem with fly ash, a rotary feeder was installed ahead of the weightbelt feeder.

Gypsum, another portion of the raw materials, is delivered by rail as is coal. All of the raw materials are stored in weather-proof enclosures and are available for transfer to the raw milling operation. In order to avoid the handling problems that are created by fly ash, a considerable amount of ingenuity was utilized to prevent the dust and other types of handling problems that have been encountered in the past when using fly ash. Each of the raw materials is stored separately as shown in the figure. The materials are then proportioned and conveyed to the raw milling processing system. In this process, the raw materials are ground to a fine powder and are conveyed to the kiln. During this process, care is taken to keep the fly ash covered at all times by conveying it with limestone on top of it so that the dust problems frequently encountered with fly ash are minimized. Wet and dry processing are shown in the figure; however, the Joppa plant used the dry processing only. In this case, the raw materials are ground, mixed with water to form a slurry, and then blended.

Since the fly ash is mixed with the other ingredients used in the manufacture of portland cement following the processing of the raw materials, the remainder of the production of cement is identical to the conventional process where burning changes the raw mix chemically into cement clinker and the clinker with gypsum added is ground into portland cement and shipped. Shipping of the cement takes place in the same barges that brought the raw material.

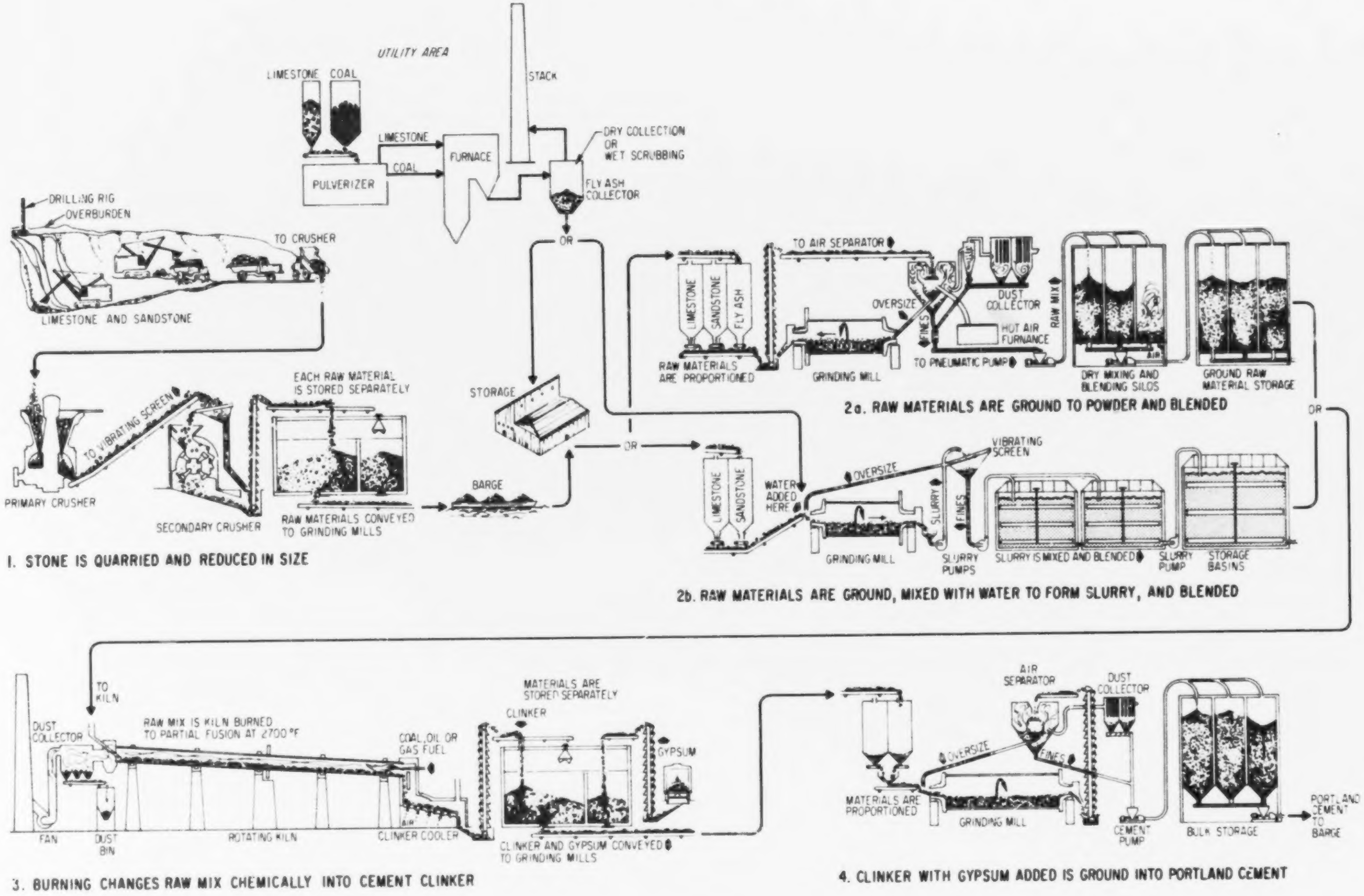
UTILITY AREA
LIMESTONE
COAL
PULVERIZER
LIMESTONE
COAL
FURNACE
STACK
DRY COLLECTION OR WET SCRUBBING
FLY ASH COLLECTOR
OR
DRILLING RIG
OVERBURDEN
TO CRUSHER
LIMESTONE AND SANDSTONE
PRIMARY CRUSHER
TO VIBRATING SCREEN
SECONDARY CRUSHER
EACH RAW MATERIAL IS STORED SEPARATELY
RAW MATERIALS CONVEYED TO GRINDING MILLS
BARGE
STORAGE
OR
1. STONE IS QUARRIED AND REDUCED IN SIZE
TO AIR SEPARATOR
LIMESTONE
SANDSTONE
FLY ASH
RAW MATERIALS ARE PROPORTIONED
GRINDING MILL
OVERSIZE
FINES
DUST COLLECTOR
HOT AIR FURNANCE
TO PNEUMATIC PUMP
RAW MIX
AIR
DRY MIXING AND BLENDING SILOS
GROUND RAW MATERIAL STORAGE
2a. RAW MATERIALS ARE GROUND TO POWDER AND BLENDED
OR
LIMESTONE
SANDSTONE
WATER ADDED HERE
OVERSIZE
VIBRATING SCREEN
SLURRY
FINES
GRINDING MILL
SLURRY PUMPS
SLURRY IS MIXED AND BLENDED
SLURRY PUMP
STORAGE BASINS
2b. RAW MATERIALS ARE GROUND, MIXED WITH WATER TO FORM SLURRY, AND BLENDED
TO KILN
DUST COLLECTOR
RAW MIX IS KILN BURNED TO PARTIAL FUSION AT 2700 °F
COAL, OIL OR GAS FUEL
AIR
FAN
DUST BIN
ROTATING KILN
CLINKER COOLER
MATERIALS ARE STORED SEPARATELY
CLINKER
GYPSUM
CLINKER AND GYPSUM CONVEYED TO GRINDING MILLS
3. BURNING CHANGES RAW MIX CHEMICALLY INTO CEMENT CLINKER
AIR SEPARATOR
DUST COLLECTOR
OVERSIZE
FINES
MATERIALS ARE PROPORTIONED
GRINDING MILL
CEMENT PUMP
BULK STORAGE
PORTLAND CEMENT TO BARGE
4. CLINKER WITH GYPSUM ADDED IS GROUND INTO PORTLAND CEMENT

Fig. E-1. Portland Cement Production

APPENDIX F

DESCRIPTION OF FLY ASH BRICK PILOT PLANT

The following figure shows a schematic diagram of the flow of raw materials and equipment layout of the fly ash brick pilot plant at the Coal Research Bureau of West Virginia University. Fly ash for the plant is stored in a 50-ton hopper which is fed with a five-inch diameter pneumatic conveyor line. Bottom ash is stored in a five-ton hopper after passing a four-ton per hour scalping screen. Oversize rejects from the screens are discarded or recycled through a secondary crusher and returned to the slag hopper. Then, 74-percent fly ash and 23-percent bottom ash or slag is mixed with 3-percent sodium silicate binder in a 13-ton per hour continuous mix-muller where the silicate bonds physically with the fly-ash. The mixture is then rapidly conveyed to a 750-ton toggle press that forms the desired shape. Green bricks from the press are then dried and fired using conventional brick dryers and kilns. Two gas operated shuttle kilns are employed, each having a acpacity of 500 bricks. The changes that take place during the firing are physical rather than chemical. As the temperature of the brick increases, the sodium silicate binder eventually becomes a viscous liquid and at the end of the firing cycle the ash components undergo vitrification.

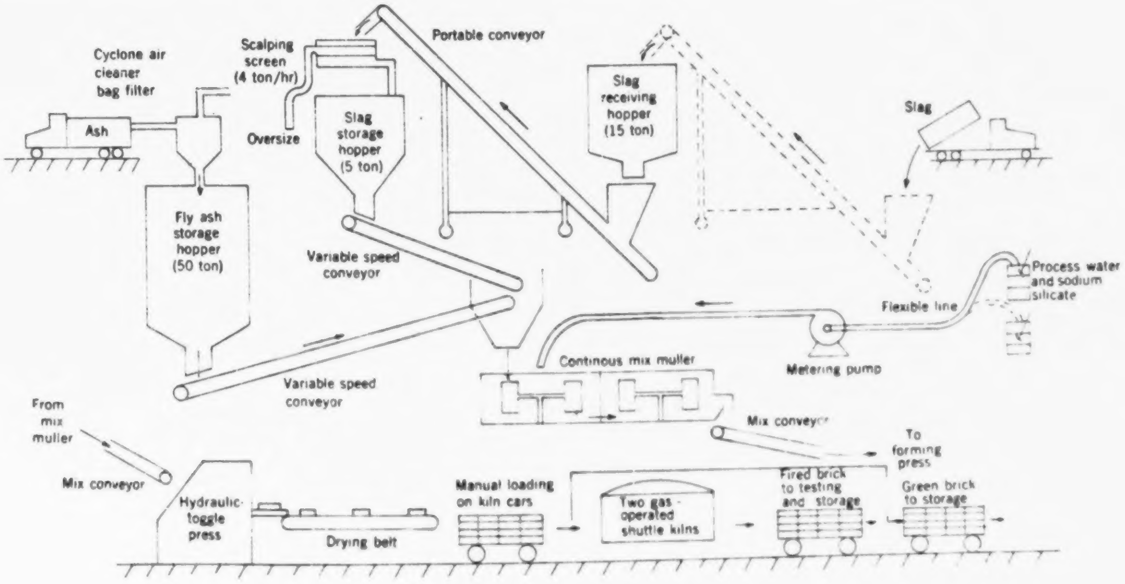
Cyclone air cleaner bag filter
Ash
Scalping screen (4 ton/hr)
Oversize
Slag storage hopper (5 ton)
Portable conveyor
Slag receiving hopper (15 ton)
Slag
Fly ash storage hopper (50 ton)
Variable speed conveyor
Process water and sodium silicate
Flexible line
Metering pump
Continous mix muller
Variable speed conveyor
From mix muller
Mix conveyor
Mix conveyor
To forming press
Hydraulic toggle press
Drying belt
Manual loading on kiln cars
Two gas operated shuttle kilns
Fired brick to testing and storage
Green brick to storage

Fig. F-1. Flow Diagram of Fly Ash-Brick Pilot Plant

APPENDIX G

DRY-COLLECTED LIMESTONE-MODIFIED FLY ASH

The trace analyses of TVA dry-collected limestone-modified fly ash performed by Shell Development Company and by Oak Ridge Laboratories are presented in Tables G-1, G-2, and G-3. These were provided by the Environmental Protection Agency's Office of Air Programs, Division of Control Systems, Process Measurements Section, and were not analyzed in this study. However, they do indicate a need for consideration of potential toxic effects in the study of the modified ash.

Table G-1. Spark Source Mass Spectrographic Analysis of TVA Dry-Collected, Limestone-Modified Fly Ash by Shell Development Company

Element	Concentration, %W in Triplicate		
Fe*	7.7	8.2	6.4
Al*	6.6	7.2	5.9
Mg*	2.0	2.0	1.7
Na*	0.55	0.57	0.43
B*	0.12	0.12	0.09
Mn	0.06	0.06	0.05
Cu	0.006	0.006	0.005
Ti	0.2	0.2	0.2
Ni	0.02	0.02	0.02
Cr	0.006	0.006	0.005
V	0.02	0.02	0.02
Si	20.0	20.0	16.0
Ca	10.0	11.0	8.0

NOTE: The general-purpose emission method of Kroonen and Vader, ("Line Interference in Emission Spectrographic Analysis," Elsevier, 1963) was used for this analysis. The calibration constants supplied by these authors were used directly to give an accuracy within a factor of two of the amount present. The elements marked (*) are believed accurate to within ± 20 percent.

Deviations observed in triplicate analyses were observed in other fly ash samples. These deviations were largely due to the inhomogeneity of the samples.

Table G-2. Dry-Collected Limestone-Modified Fly Ash Trace Analysis* by Shell Development Company

Element	Concentration (ppm)
As	250
Br	12
Sm	27
Ba	7000
Zn	500
Cr	55
Lu	20
Co	10
Sc	7
Sb	4
Cs	3
Hf	2
Yb	1
Ta	0.5

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*Determined by neutron activation and atomic absorption

Table G-3. Oak Ridge Spark Source Mass Spectrometry Analysis of TVA Dry-Collected Limestone-Modified Fly Ash

Element	Throttle Number[*]					
	—	0	4	12	16	18
As	100	200	100	100	200	50
B	300	300	500	500	500	500
Ba	200	200	200	200	200	200
Be	2	2	1	2	2	2
Cd	<5[**]	<5	<5	<5	<5	100
Cr	130	130	130	130	300	300
Cu	130	150	150	200	200	200
Mn	190	200	240	290	390	500
Na	9400	9000	8000	9100	9600	8400
Ni	200	300	200	200	300	300
Pb	300	300	200	300	300	500
Sb	<3	<3	<3	<3	<3	<3
Sr	200	250	250	250	250	300
Tl	<5	<5	<5	<5	<5	5
Ti	3600	3500	3500	4100	4600	4200
V	200	200	200	200	200	200
S	>5000	>5000	>5000	>5000	>5000	>5000
Hg	<5	<5	<5	<5	<5	<5
Se	<10	<10	<10	<10	<10	<10

[*] "0" equals 28.7 microns
"4" equals 25.8 microns
"12" equals 12.8 microns
"16" equals 4.52 microns
"18" equals 1.5 microns

[**] "5" is lower limit of detection

APPENDIX H

SAMPLE SPECIFICATION AND USE DATA FOR FLY ASH AS AN ADMIXTURE IN CONCRETE FURNISHED BY THE TENNESSEE VALLEY AUTHORITY DIVISION OF ENGINEERING DESIGN

H. 1 GENERAL DISCUSSION

The following documents, which are included in this appendix, provide a basic indication of the approaches taken by the TVA for the development of specifications and utilization of fly ash as an admixture in portland cement concrete:

1. Excerpt from Construction Specification G-30. This provides a description of the TVA method of classifying fly ash based on properties data. Further information for testing, curing and application is provided in the complete specification and in the TVA Specification G-2, "General Construction Specification for Plain and Reinforced Concrete," dated February 10, 1970.
2. Some typical sample proportioning data are provided which identify actual applications in the TVA system. Many other applications of different proportioning exist.

These data are provided for information only, and no endorsement is intended. However, this approach to the usage of fly ash in large quantities economically is considered significant since it provides appreciable detail pertaining to one of the most advanced uses exhibited for fly ash in concrete. It is interesting to note that according to the TVA Division of Engineering Design that

> "TVA does not differentiate in the curing requirements for different classes of concrete nor do we require any unusual or extended curing for fly ash concrete over what is normally considered acceptable for regular portland cement concrete without fly ash. We require all concrete to be protected from excessive loss of moisture for a minimum period of 14 days.
>
> "TVA has been using fly ash in all major construction projects since 1957. During this time we have not encountered a single service problem which, in any way, could be attributed to the presence of fly ash in the concrete. As a matter of fact, fly ash concrete has significantly been free of service problems of any kind.
>
> "The recent trend in usage of fly ash concrete in TVA is to specify more 90 and 180 day strength requirements in order to utilize the age-strength advantage of fly ash in concrete."

This technology is applied not only to mass concrete but to building construction as well. This approach, therefore, should serve as a basis for the development of a new set of specifications which could apply to the total concrete industry, thereby eliminating the confusion which results from the various existing specifications which conflict and do not recognize the relevancy of the classification of fly ash to usage.

A comparison of existing specifications is given in Table 4-8, and a discussion of proposed specification modifications which require further efforts is given in Section 4.3.3.6.

EXCERPT 1

TVA SPECIFICATION

TENNESSEE VALLEY AUTHORITY
DIVISION OF ENGINEERING DESIGN

ALL PROJECTS

GENERAL

CONSTRUCTION SPECIFICATION

NO. G-30

FOR

FLY ASH FOR USE AS AN ADMIXTURE IN CONCRETE

March 16, 1970

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APPROVED
Director of Construction

APPROVED
Director of Engineering Design

GENERAL CONSTRUCTION SPECIFICATION NO. G-30

FOR

FLY ASH FOR USE AS AN ADMIXTURE IN CONCRETE

1.0 General

This specification has been coordinated with the Division of Construction and the Office of Power. These specifications cover the use of fly ash as an admixture in concrete. Fly ash from TVA plants is separated into three classes based on the fineness of the ash and the resultant contribution of the fly ash-cement combination to the strength of concrete. All three classes are acceptable for use; however, mix alterations may be required in the concrete any time a change occurs in class of fly ash or source of supply. (Collection from generating units with different type precipitators also constitutes change in source.) Ash shall be collected only from units operating as base power units.

2.0 Class and General Use

Class I - Fine Fly Ash - This provides the maximum strength contribution at all ages for given proportions of fly ash to cement. When properly proportioned, it is well suited for use in any class of concrete and is particularly suited to requirements for high concrete strength and for early concrete strength.

Class II - Medium Fly Ash - This class provides good strength contribution at ages up to 28 days and very good strength contribution at 90 days or more for given proportions of fly ash to cement. When properly proportioned, it is well suited for use in any class of concrete.

Class III - Coarse Fly Ash - This class provides low strength contribution at ages up to 28 days and good strength contribution at 90 days or more for given proportions of fly ash to cement. Delivered cost must be low for economical use in 28-day strength concrete; however, when properly proportioned, it is well suited for concrete having strength requirements below 4000 psi at 90 days or more. Greater fluctuations in air content can be expected, requiring more frequent testing of air content for control with this class than required with the fine or medium fly ashes.

3.0 Recommended Mix Alterations

The amount of cement required and economic proportions of fly ash to cement for each particular class of concrete should be established by trial mixes. When a change in class of fly ash is anticipated, the following table gives the relative adjustments in cement content for equal strength concrete. These adjustments should be used until routine tests establish a more accurate adjustment.

RELATIVE ADJUSTMENTS IN CEMENT CONTENT

Concrete		Class of Fly Ash		
Strength, PSI	Age in Days	I	II	III
2000	28	100	103	112
3000	28	100	104	114
4000	28	100	105	116
5000	28	100	106	-
2000	90	100	100	106
3000	90	100	101	108
4000	90	100	102	110

4.0 Chemical Requirements

The chemical requirements for all three classes of fly ash are:

Silicon dioxide (SiO_2); plus aluminum oxide (Al_2O_3); plus iron oxide (Fe_2O_3), minimum percent	75.0
Magnesium oxide (MgO), maximum percent	5.0
Sulfur trioxide (SO_3), maximum percent	4.0
Loss on ignition, maximum percent	6.0
Moisture content, maximum percent	3.0
Available alkalies as Na_2O, maximum percent	2.0

5.0 Physical Requirements

	Class		
	I	II	III
Fineness, surface area, cm^2/cm^3, minimum	6500	5000	3500
Pozzolanic activity index:			
With portland cement at 28 days, minimum percent of control	85	70	55
With lime at 7 days, minimum psi	1000	800	600

5.0 Physical Requirements (continued)

	Class		
	I	II	III
Fineness index: Amount passing when wet-sieved on No. 325 (44 um) sieve, minimum percent	88	78	68

6.0 Sampling and Testing Requirements

Trial mix program

Fly ash from potential sources of supply shall be sampled by the Singleton Materials Laboratory and tested for all specification requirements and identified as to class prior to use by any project.

Project testing

Fly ash shall be sampled at the construction site at a minimum rate of one sample for every three truckloads delivered. Each sample shall be tested in the field for identification of class of fly ash by either the percent passing No. 325 sieve or the sedimentation test. Since these two tests are only indications of fineness, periodic samples must be sent to Singleton for complete physical testing to assure correlation of fly ash identification. For shipment and identification these samples shall be sealed in plastic bags, dated, and numbered consecutively.

Any time individual field laboratory tests exceed the specified limits for a given class or exceed the average of previous sedimentation tests by more than 5 cc or the average percent passing the No. 325 sieve by more than 5 percent, concrete mixes shall be adjusted as needed for the next lower class of fly ash.

Office of Power testing

The Office of Power shall be required to sample all units furnishing ash to TVA projects at a minimum rate of one sample per month as long as shipments are made. Complete physical tests are required from each sample for identification of class. Complete chemical tests are required from every twelfth sample or any time a change in class is indicated by the physical tests. Six copies of all test results shall be supplied for distribution to each project using the ash.

EXCERPT 2

SAMPLE TVA FLY ASH CONCRETE USAGE DATA

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Project - Sequoyah Nuclear Plant
Construction Start - 1970
Construction Complete - 1974*

Class of Concrete		203BFW	201.5BFW	301.5BFW	301.5AFW	401.5AFW
Required Strength (psi)		2000	2000	3000	3000	4000
Age for Req. Str. (days)		90	90	90	28	28
Mix proportions						
Cement	(lbs)	135	160	220	310	441
Fly ash	"	190	220	220	185	110
Water	"	155	190	201	210	230
Sand	"	1127	1405	1270	1246	1214
3/8" coarse aggregate	"	182	297	297	297	290
3/4" " "	"	425	693	693	693	676
1-1/2" " "	"	660	1076	1076	1076	1050
3" " "	"	1273	-	-	-	-
WRA & AEA						
**Air content	%	4.5	5.5	5.5	5.5	5.7
Slump	Inches	2	1.5	2.5	2.5	3.5
(Average Compressive Strength in psi)						
at 28 days		1600	1600	2700	3950	4900
at 90 days		3600	3350	4300	*5600	*6300
at 180 days		*4100	*4100	*5200	*6400	*7000
Class of Fly Ash		I	I	I	I	I
Where used (type of structure)						
Reactor Building		X	X	X	X	X
Auxiliary Building		X	X	X	X	X
Control Building		X	X	X	X	
Turbine Building		X	X	X	X	
Service Building				X	X	
Office Building					X	

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*Estimated
**Portion passing a 1-1/2-inch screen

Project - Tellico Dam
Construction Start - 1967
Construction Complete - 1968

Class of Concrete	203CFW	303BFW	301.5BFW	301.5AFW
Required Strength (psi)	2000	3000	3000	3000
Age for Req. Str. (days)	180	90	90	28
Mix proportions				
Cement (lbs)	110	210	240	290
Fly ash "	208	126	192	174
Water "	150	160	190	205
Sand "	1144	1100	1365	1360
3/8" coarse aggregate "	240	240	355	355
3/4" " " "	480	480	658	658
1-1/2" " " "	795	795	1086	1086
3" " " "	1140	1140	-	-
WRA & AEA				
**Air content	5.5	7.0	6.5	6.5
Slump	2.5	2.75	3.0	2.75
Average Compressive Strength in psi				
at 28 days	1430	3620	3280	4100
at 90 days	3540	5520	5050	5900
at 180 days	4320	-	-	-
Class of Fly Ash	I	I	I	I
Where Used (type of structure)				
Non-overflow (mass)	X			
Non-overflow (face)		X	X	
Spillway (mass)	X			
Spillway (face)			X	X

**Portion passing a 1-1/2" screen.

Project - Paradise Steam Plant - Unit 3
Construction Start - 1966
Construction Complete - 1968

Class of Concrete		301.5BFW	301.5AFW	351.5AFW	400.75AFW
Required Strength	(psi)	3000	3000	3500	4000
Age for Req. Str.	(days)	90	28	28	28
Mix proportions					
Cement	(lbs)	270	338	450	517
Fly ash	"	108	152	135	130
Water	"	220	227	256	270
Sand	"	1284	1284	1230	1195
3/8" coarse aggregate	"	305	294	268	580
3/4" " "	"	610	587	535	1180
1-1/2" " "	"	1127	1080	990	-
WRA & AEA					
Air content	%	5	5	5	5.5
Slump	Inches	2.5	2.5	4.0	4.0
Average Compressive Strength in psi					
at 28 days		3030	3840	4860	5050
at 90 days		4110	5350	6150	6400
at 180 days		*4800	*5900	*6800	*7000
Class of Fly Ash		II	II	II	II
Where Used (type of structure)					
Powerhouse		X	X		
Intake Tunnel				X	
Chimney					X
Cooling Towers					X

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*Estimated

Project - Wheeler Lock
Construction Start - 1960
Construction Complete - 1963

Class of Concrete		306AFW	301.5AFW	401.5AFW
Required Strength	(psi)	3000	3000	4000
Age for Req. Str.	(days)	28	28	28
Mix proportions				
Cement	(lbs)	245	415	590
Fly ash	"	168	208	66
Water	"	185	246	320
Sand	"	720	950	1035
3/4" coarse aggregate	"	310	1045	805
1-1/2" " "	"	515	1075	1035
3" " "	"	750	-	-
6" " "	"	1130	-	-
WRA & AEA				
**Air content	%	6.5	6.0	6.5
Slump	Inches	2.5	2.5	3.25
Average Compressive Strength in psi				
at 28 days		3400	4240	4720
at 90 days		4600	5200	-
at 180 days		*5300	*5900	-
Class of Fly Ash		III	III	III
Where Used (type of structure)				
Lock Walls		X	X	
Floating Approach Wall				X

Note: Strengths listed are 10% less than actual test strengths to compensate for air removal in rodding cylinders based on comparative strengths of air entrained concrete rodded specimens vs drop table specimens.

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*Estimated
**Portion passing a 1-1/2 inch screen